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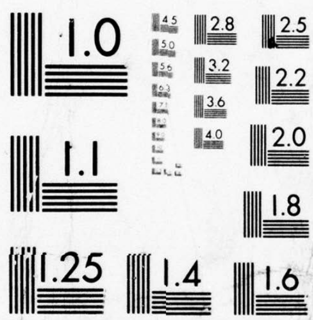

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Memorandum No. M-134

HYDRODYNAMIC STUDIES FOR A LARGE, HIGH-SPEED, VARIABLE PRESSURE, FREE SURFACE FLOW FACILITY

by
John F. Ripken,
Joseph M. Wetzel,
and
Loren M. Bergstedt

This study was sponsored by the
Ship Performance Department of the
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Subproject ZF 199 0203
Contract N00014-67-A-0113-0027

August 1973
Minneapolis, Minnesota

University of Minnesota

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HYDRODYNAMIC STUDIES FOR A LARGE, HIGH-SPEED, VARIABLE PRESSURE, FREE SURFACE FLOW FACILITY

I. INTRODUCTION

The naval surface ships of the future will operate at progressively greater speeds which will entail increasingly serious hydrodynamic problems. Although analytical solutions to these problems will also progress, model studies will continue to provide much of the practical understanding of new high-speed design concepts. Accordingly, the potentials of naval model test facilities must be upgraded from time to time to provide for these future needs. To this end, definitive action, based on preliminary studies which had been under way at NSRDC for several years, was begun in 1971 to determine whether existing NSRDC facilities could be satisfactorily upgraded. As part of this effort the St. Anthony Falls Hydraulic Laboratory contracted in September of 1971 for a study of the feasibility of upgrading the performance potentials of the existing 36 inch cavitation tunnel at NSRDC. This study led to a feasibility report* which concluded that the 36 inch tunnel could not be practically adapted to provide the desired performance capabilities, but that these needs could probably be fulfilled by a new channel facility. of the form shown in Fig. 1. An extensive model testing program was advocated to develop a design for such a facility. The program was implemented by contract extensions covering the period from May 1972 through August 1973. This report summarizes the findings of this model test program. The model employed for the tests is shown in Fig. 2.

The objective of this program was the hydrodynamic delineation of a test facility having a test section with the following dimensions and flow characteristics:

Depth:	approximately 3 ft
Width:	3 ft
Length:	approximately 20 ft
Speed Range:	From zero to 100 fps
Free Surface:	Essentially planar and wave-free at all speeds above critical ($V_c \approx 10$ fps)
Velocity Profile:	Essentially flat over 85 per cent of the cross-sectional area

*Ripken, J. F.; Wetzel, J. M.; and Schiebe, F. R., A Hydrodynamic Feasibility Study for a Large, High-Speed, Variable Pressure, Free Surface Water Test Facility, Memorandum No. M-132, St. Anthony Falls Hydraulic Laboratory, Univ. of Minnesota, April 1972. AD A040035

Turbulence Level:	Minimal to simulate an infinite prototype flow field
Pressure Range:	From near vapor pressure to 2 atmospheres absolute including operating Sigma values down to 0.02
Free Gas Content:	Minimal observational impairment, non-critical dynamic effects, adequate nucleation
Free Gas Capacity:	Ingest at test section exit and remove up to 200 cu ft/min. of air supplied by venting or exhaust of test models
Flow Stability:	Essentially steady state or devoid of low frequency pulsations or drift

Figure 3 depicts the form and major dimensions of the channel test facility which resulted from this study and defines the flow lines of constituent parts of the channel loop. These parts are treated more fully in separate sections in which additional dimensional details are given for each part. The design dimensions are derived from both prior art and new designs built and tested on a complete operating model channel of size ratio 1:4.8. Because this model was assembled largely from existing available components, the model as shown in Fig. 2 does not agree in all dimensions with the proposed final recommendations of Fig. 3. The differences are most notable in the first diffuser and elbow, which were shorter and smaller in the model version.

Included in Fig. 3 are the major dimensions of an alternate test section which may be added to the proposed tunnel at some later date. This alternate section would provide a 4 ft deep by 6 ft wide by 35 ft long flow facility for variable pressure model tests of larger assemblies of components at speeds up to 50 fps. No tests were run on this proposed alternate, although suggested major boundary dimensions are given in Fig. 40 and some features are discussed in Section XIII.

II. TEST SECTION

The test section, depicted as tunnel component II in Figs. 3 and 4, is in cross section a simple rectangular box with horizontal floor and roof, vertical side walls, and generously rounded lower corners. It begins at the terminus of the contraction exit and ends at the skimmer entrance. Dimensional and operating features of the test section are discussed in the sections which follow.

A. Width

It is recommended that the nominal width of 3 ft which was specified be maintained constant for the 20 ft length of the test section, with no attempt being made to taper to compensate for a growing boundary layer displacement. In the model the 3 ft (prototype) flow section width was maintained from the floor to the roof of the air chamber. These arbitrary dimensions were a compromise between providing adequate space for housing and manway access to the models and instrumentation and providing for a minimal elastic air dome above the water. Variations of the topside width and height are not considered critical, although they were not model tested.

B. Depth

The specified prototype depth of 3 ft is nominal only. The depth of the flow entering the model test section was made to be slightly controllable by altering the length of the top of the contraction nozzle exit which slopes downward at 30° toward the test section. To provide for such control and to assure the maintenance of a finely machined sharp edge at this terminus, the last portion of the contraction lip was made replaceable in the model, as shown in Fig. 4, and this construction is advocated for the prototype. Because the contraction lip slopes at an angle of 30° with the horizontal, the issuing free water surface continues to contract for a significant distance before flattening and becoming parallel to the test section axis. This contracting length is approximately 2 times the test section depth, or about 6 ft prototype. On the basis of the model study it is recommended that in the prototype, the sharp-edged terminal lip be placed 3 ft 6.85 in. above the floor to produce the desired 3 ft depth. Provision should be made for this height to be varied by about $\pm$ 5 per cent through the use of alternate lip block lengths ranging from zero to about 6 inches.

From the end of the free surface contraction the depth begins to rise slightly in response to the displacement caused by the growth of the boundary layer. Model observations of the axial variation in depth or water surface gradient are shown in Fig. 5a, and lateral variations in depth are shown in Fig. 5b. Additional statements relating to these gradients are included in sections II-I-1 and II-I-2. On the basis of this it is recommended that in the prototype the surface skimmer at the downstream end of the test section be set at a mean value of 3 ft above the floor with provisions for adjustments of ± 5 per cent.

In the proposed design no provision has been made for major variations in the depth. Consideration was given, in early studies, to including major depth change as a possible test variable. However, in view of the high test velocities proposed it was considered unwise to complicate the flow boundaries with variable depth provisions. The test section as evolved does not preclude the possibility of future additions of fixed liners in the contraction, skimmer, and diffuser to accomplish this. No definitive plans or model tests were made for such concepts.

C. Length

The 25 ft test section length shown in Fig. 4 is greater than the nominal length of 20 ft originally required by the NSRDC specifications for meeting their eventual test needs. As the foregoing discussion of test section depth indicates, model development studies have established that approximately the first 6 ft of this test section length experiences significant depth change due to contraction effects. The useful free surface is foreshortened accordingly. However, at the downstream end of the nominal test section there are approximately three additional feet of free surface length between the end of the test section and the skimmer lip. This length, and possibly even more, will on occasion be disturbed by skimmer control functions. Thus the 25 ft shown in Fig. 4 is an arbitrary compromise which should assure a full test length of 20 ft for most conditions.

D. Floor

In the proposed prototype test section a horizontal floor with no drainage slope or slope compensation for boundary layer growth is recommended. The proposed design includes a generous radius fillet in each corner where the side walls join the floor. For the prototype this radius

has been taken as approximately 1/4 of the section width, or 8.3 inches. These radii are extensions of similar fillets in the corners of the contractions and are intended to inhibit the disturbing corner vortices which have frequently been observed in square-cornered contraction works. The proposed fillet terminates gradually, leading into a square corner at the downstream end of the test section. The transition from round to square was model tested for a transition length equivalent to 3 ft prototype. No cavitation or other undesirable flow effects were observed to be caused by the simple transition of the corner fillet. In the model the fillet was a bolt-on addition to a square-cornered box. Either a rolled structural corner or a bolt-on corner could be used in a prototype construction, although the latter type is believed to provide somewhat better dimensional control.

E. Surface Finish

The high test section velocities intended will, together with low test pressures, promote severe cavitation conditions on all test section flow surfaces. This will necessitate high quality surface finishes and joint alignments. Due to the large size of the test section it will not be practical to machine finish all contact surfaces, and it will probably be necessary to fabricate most surfaces using weldment and essentially "as is" stainless steel clad plate. Suggested surface finish specifications for the test section are included in the tabular summary of Fig. 39.

F. Auxiliary Physical Features

Operation of the test section will require that its surfaces be provided with a number of breachings and appendages ranging from small instrument taps to major openings. These include

1. Visual Access

Visual access to the test section for both observation and photography is desirable on one or both walls for most of the test section length. For the model tests with pressures ranging to $\pm$ one atmosphere, one large window in one wall together with three small ports in the roof allowed adequate observation for test purposes and presented no structural problems. However, for the proposed large prototype, which is to have a pressure range of -1 to +4 atmospheres relative, structural problems will be more serious. In consequence, window area may have to be more limited. Viewing windows in

contact with high speed flow must be flush fitted in surface alignment and edge fitted with minimum gap if edge cavitation is to be avoided. This is particularly true near the upstream end.

2. Man Access

Ready man access through the walls or roof to permit model installation and maintenance should be provided. However, model operations have indicated that flow instabilities may be triggered by a number of operational possibilities and that such instabilities may lead to flooding of the entire test section chamber. With high speeds this may be a violent flow process, and it is not recommended that provision be made for personnel to be in the chamber during operation.

3. Model and Equipment Access, Mounting, and Protection

Smaller test models and equipment may fit through the manway hatches, but on some occasions larger openings than would normally be available in manways may be required. The model has thus been provided with a large removable hatch in its roof. Similar provisions, including crane handling facilities, should be made in the prototype. As was indicated earlier, the test section chamber may be subject to violent flooding. Accordingly, all equipment mounted in the test section must be able to withstand flooding and severe water forces. It is recommended that the roof and above-water areas of the test section walls be provided initially with a liberal distribution of substantial bolt anchorages for the future attachment of appendages and equipment support.

In the channel studies conducted for this report a number of the sub-studies necessitated tests which involved inserting various test configurations in the model test section. For this purpose a basic streamlined support strut and cylindrical nacelle were provided as shown in Fig. 6. This system was employed for tests as follows:

a. For injecting substantial quantities of air into the channel for studies of its influence on stability of velocity (see section II-G-7).

b. For mounting drag discs to increase flow resistance in energy evaluations (see section VIII).

4. Pressure Relief

Prior experience with recirculating water tunnels has shown that operational problems sometimes cause severe pressure surges. These have blown viewing windows and caused other structural failures. Given the large energy content of the test section jet (16,000 HP at $V = 100$ fps) and the large, relatively unstable free surface that will exist in the free surface tunnel, pressure surges due to operational malfunctions may be quite substantial. To avoid structural damage, a relief valve of substantial capacity is needed. Since dynamic conditions will permit the test section to operate with lower pressures than the rest of the tunnel loop, the test section is a logical location for sensitive relief venting. In the model tunnel, in which the test section was exposed to $\pm$ one atmosphere relative, the relief vent was designed for a 20 psi rupture differential. The relief vent in this case consisted of a suitable plastic diaphragm mounted between the flanges of an 8 inch pipe. This pipe was attached near the upper corner of the back wall of the test section near the upstream end. The other end of the short pipe was vented to the outdoors. Despite numerous violent floodings of the test section during model test operations, this rupture diaphragm did not become loaded enough to vent. Since prototype test pressures, like those in the model, will rarely exceed one atmosphere relative, a similar low pressure relief setting is suggested for the prototype. For the rare tests at higher pressures a higher rupture disk setting could be used. Rupture disks are commercially available in a wide variety of sizes and pressure differentials.

5. Supercharge and Air Return

The application of a vacuum or compressed air to the tunnel in order to control or supercharge the ambient pressure is most advantageously accomplished by tapping in to the test section air dome. A connection at any convenient high level point near the upstream end of the test section chamber is considered satisfactory in that it will not disturb the water flow or ingest water into the vacuum system. Since normal operations of a tunnel do not require high rates of transient variation in ambient pressure, the required gas tap, air plant, and vacuum plant can all be of modest capacity. This auxiliary plant will be discussed further in Section XIV.

Normal operations of the skimmer and many types of test bodies will entrain substantial quantities of air into the flow. The NSRDC specifications require that the tunnel be capable of ingesting and subsequently separating out not less than 200 cu ft per minute as a consequence of test conditions. A small part of this volume will be returned to the test section directly through the return vents of the skimmer system, but most of the gas must be extracted from the water in the gas separator and recirculated by piping back to the test section. For this purpose the gas dome in the test section must be tapped for an air flow return line of sufficient capacity to permit entrance without significant disturbance. In the model this entrance was provided by a valved 1-inch pipe on a side wall at the extreme downstream end of the channel. This location was selected because of the possibility that in some cases water might be blown back with the returning air, and this water would be least disturbing if released over the skimmer. Such watered releases have been seen during window observations in the model. The size of this return line is considered in section XIV-H-1.

6. Piezometer Tap for Speed Indication

In the case of a free surface tunnel the pressure in the domed gas should be employed to measure the velocity. A simple pressure tap anywhere high on the walls or roof near the upstream end of the test section should be satisfactory.

7. Splash Guard

Maintenance of a high quality water surface in the test section requires that disturbance sources be minimized. One such source is splash-back water originating from the normal actions of test models or of the downstream skimmer. Most sprayed or splashed water is dominantly directed downstream, and substantial upstream backsplash is the result of rebound from either the skimmer mechanism or the downstream end of the test section chamber. To minimize this return a splash guard has been provided for just upstream of the skimmer drum. This guard is to consist of nine tent-shaped struts, each having a symmetrical triangle cross section with a height of 6 inches, a base width of 3.5 inches, and a length of 5 ft, 6 inches welded to a heavy bar frame which is bolted to the side walls. The wedge-shaped bars are to have a clear space of approximately 5/16 inch between them. The elements of this assembly are shown in Fig. 4.

G. Velocity Operating Characteristics

1. Range

The velocity range requirements are nominally zero to 100 fps. Actually, the available forms of pump drive probably will not permit effective speed control at speeds near zero. Moreover, speeds of less than 10 fps will provide sub-critical energy conditions with a 3 ft flow depth, and the resulting gravitational wave disturbances will prove troublesome in the free surface. Low speed tests may also require an increase in the test section depth to compensate for shifts in the free surface contraction. Therefore a workable minimum test speed of 5 fps is more significant than speeds closer to zero.

The selected maximum speed of 100 fps is a workable compromise between testing possibilities and the mounting fluid dynamic problems that accompany high speed performance. These problems result from the fact that dynamic pressures increase as the square of the velocity and driving energy requirements increase as the cube. Both of these factors ultimately pose problems in the designing of the recirculating pump.

2. Starting Conditions and Control

The flow speed is to be controlled through the adjustment of both the blade angles and the shaft speed of the recirculating axial flow pump. For stability of velocity it is essential that the pump blade mechanism be capable of maintaining any desired preset angular value within its range. Moreover, it should be possible to preset the pump rpm and maintain it automatically. An infinitely variable control capability is desired in the upper 95 per cent of the control range and the best attainable control in the remaining 5 per cent of the range. The required constancy of the speed setting in the upper 95 per cent is $\pm$ 0.1 per cent at any setting, with the best constancy attainable sought for the remainder of the range.

3. Measurement

The most satisfactory method in common usage of evaluating the mean test section speed in a water channel is measuring the pressure drop across the contraction upstream of the test section. This pressure value, together with a suitable continuity equation, permits solution for the test section speed through application of a Bernoulli energy equation. In the model

study, the pressure was read from a simple manometric system fitted to a tap upstream of the contraction and another tap fitted to the test section gas dome. Since the contraction ratio of the proposed channel is unusually high (approximately 100 to 1), the potential for a high degree of measurement accuracy is unusually good. It should also be noted that use of the test section gas pressure over a free surface provides a velocity value that applies over the entire length of the test section core flow. This is in contrast to a uniform closed jet test section, wherein the core flow must accelerate to accommodate the displacement effects of the growing boundary layer.

4. General Stability

One important factor in a water channel test is the constancy of a selected velocity value. To promote such stability, rather severe specifications are laid down for the operational stability of the pump blade angle setting and the shaft speed. These specifications have been described previously and are the principal controls that can be exercised. Tests in the model indicate that the stability of control is generally quite satisfactory. This is attributed principally to the relatively large mass of water involved in a channel flow circuit containing an air separator of the type employed in this case. This large mass provides a substantial flywheel effect which suppresses or inhibits rapid changes and thus contributes to stability.

The model studies have disclosed two potential causes of instability or drift that must be allowed or compensated for. Both are associated with the elastic effect brought on by air in the flow circuit. The first is the presence of air in collected volumes in the test section dome and at other high points in the recirculating loop. These collected volumes are capable of some degree of elastic pulsing and possible resonance from a variety of sources. The simplest way of treating these centers of instability is in general to minimize their presence or volume. The air which may tend to collect in the crown of the first elbow downstream of the test section should be prevented from collecting through provision of a venting pipe to return air to the test section dome. In addition, the dome of the gas separator will collect air. This dome may in some instances be operated with a minimum volume and rapid return of all separated gas to the test section. In other instances, it is desirable to have a substantial volume

of gas in the separator dome to provide displacement space for the tunnel water when large quantities of gas are introduced into the flow. Limited tests in the model indicate that venting of the gas from the separator collection dome to the test section dome may require some type of modulated rate control. Undamped venting of the gas returning to the test section led in some instances to the generation of pulsing in the domed gas both in the separator and in the test section. This in turn generated large-sized waves on the test section surface with oscillations at the skimmer which triggered flooding of the test section. This undesirable instability was readily controlled for near steady state conditions by suitable throttling of the air returning from the separator. Whether stability can be readily achieved in test models which breach, vent, or exhaust with rapid rates of change has not been determined in the limited model tests conducted to date. Further information relating to preferred air volumes and control is to be found in section XV.

The second situation in which the elastic effects of free air create a problem is that which exists when the air content in the water flow is high. This case is treated separately under item 7 below.

5. Turbulence

The level of turbulence of the flow entering the test section should be as low as is practical in order to provide optimum test conditions. Fortunately, the presence of the very large gas separator with small tubes just upstream of the contraction tends to lower the scale of the approach turbulence and provide good decay time. This turbulence will, upon entering the very large ratio (areas 100 to 1) contraction, inherently tend to diminish the u' or transient portion of the axial component of the velocity and will amplify the v',w' lateral components. Because of the difficulties encountered in measuring turbulence in water as impure as existed in the model facility, no attempt was made to quantify the turbulence characteristics.

6. Velocity Distribution

Because of the very high area contraction ratio (approximately 100 to 1) employed in the design of this facility and the very flat velocity profiles obtained in a pilot model study of the contraction, there was every reason

to believe that the observed profiles for this model study would be very flat. It was, therefore, rather surprising when the model test profiles of Fig. 7 were first established. These profiles were measured with a flattened Pitot tube of 1/8 inch diameter. The tube was attached to the downstream end and bottom of a streamlined flat support plate. The plate had an axial dimension approximately equal to the channel depth. During the course of measuring the vertical profile of Fig. 7 it was noted that the manometer measuring the nozzle pressure drop had a small progressive drift as the Pitot tube was traversed from top to bottom. Because the inching speed controls of the model channel drive are relatively crude, fine adjustment of motor speed is not possible, and no attempt was made to correct the basic test section velocity. In consequence, the frictional resistance of the Pitot support plate varied with the insertion depth and significantly influenced the channel flow to the end that the velocity profile was skewed as shown. Later tests attempted to establish the profile for a velocity of 50 fps, but the drift in nozzle pressure differential was considered excessive, and motor speed adjustment was attempted. This proved too erratic, and the test was abandoned.

In the pilot model study, which used a gravity flow nonrecirculating system, frictional resistance in the channel did not influence the inflow, and the velocity profile was very flat. Similar flatness can be expected in the eventual prototype if the system is provided with sufficiently sensitive pump controls and if these are activated to maintain a stable pressure differential across the contraction nozzle.

The horizontal velocity profile of Fig. 7 was also disappointing in showing a slight asymmetry. This asymmetry is believed to be linked to similar evidence shown in the lateral surface slopes of Fig. 5b and, as is discussed in section II-I-2, is attributed to the slight axial mis-alignment between the nozzle and the test section. The data of Fig. 7 indicate the usual tendency of the boundary layers along solid walls to thicken with increasing flow length.

7. Influence of High Air Content

Pumps are not usually required for operation with significant quantities of air in the entering flow. In view of the substantial air flows anticipated in the proposed facility, it was considered desirable to know

whether the introduction of abnormally large quantities of air into the circuit would produce a significant shift in the test section velocity for a fixed pump operating condition. This was checked by inserting into the test section the strut and nacelle shown in Fig. 6 and discussed in section II-F-3. The upstream end of the nacelle was fitted with a sealed plug and the downstream end was left unplugged. The nacelle was mounted in the test section with its downstream end positioned about one depth unit (7-1/2 inches in the model) upstream of the skimmer. Compressed air was then released in metered amounts into the upper end of the strut and vented to the tunnel flow at the rear of the nacelle. The metered air flow was varied from zero to 0.4 per cent by volume (equivalent to the specified 200 cfm of air at the maximum prototype water flow of 100 fps). Evaluations were conducted at three arbitrary test section velocities (30, 50, and 70 fps) and with the test section held at atmospheric pressure. The air was metered to provide volume measurements which were then adjusted to test section pressure. During the process of increasing or decreasing the air flow from zero to a selected volume in the test range, the preselected differential pressure across the velocity measuring manometer was monitored. Maximum deflections were noted and interpreted as velocity changes. The resulting relation between the volume of gas injected and the ensuing change in velocity is plotted in Fig. 8.

These tests indicate that the injection of air into the test section in the amounts required by the specifications does not have a significant effect on the basic test section flow.

H. Pressure Operating Characteristics

1. Range

The pressure range required by the NSRDC specifications is from near vapor pressure to 2 atmospheres absolute at the test section water surface. Since the range of probable operating water temperatures lies between 60° and 100°F, the minimum pressure will correspondingly be between about 0.25 and 1.00 psia. These values are dependent on the available vacuum plant and may be difficult to achieve in practice because of air leakage possibilities in the large prototype structure. However, values of about 1.5 psia were achieved in the model channel without undue difficulty, this value being limited by the vacuum pump's limitations.

The upper limit of the pressure range of 2 atmospheres absolute exceeds the requirements for all normal tests, but might find ultimate use in an all-purpose facility. The primary reason for specifying the high value is that when the large components of the pressure housing of such a facility are designed for negative or vacuum pressures, they will also sustain approximately 3 atmospheres of positive pressure. In consequence, the specified 2 atmospheres of absolute pressure will not involve additional costs for most of the tunnel elements.

2. Control

The pressure control system will provide for pre-setting and automatic maintenance of the pressure in the test section. The pressure will be kept within 1/2 of 1 per cent of the setting over the range of 5 to 60 psia and within 1/2 of 1 per cent or 0.01 psi, whichever is greater, below 5 psia. It should also be made possible to temporarily divert the pressure control to the gas dome of the gas separator. Such a diversion may prove useful for various operational problems.

Considerable capacity should be provided in the controls and the compressed air and vacuum connections to permit a moderately quick response when changes are desired. These values are discussed in section XIV.

3. Measurement

The channel boundaries should be liberally provided with pressure measuring taps in regions where pressure evaluations may ultimately be needed. In general these regions would be in the test section and in the vicinity of the pump. The taps should be of sufficient size to allow measurement of both mean pressures and transients. The pressure tap for the main pressure control of Item 2 above should be placed in the domed gas above the test section, preferably high on the upstream end of the chamber to minimize water flooding. Read-out of transient values of this pressure should be routinely possible so that preferred ways of modulating air flow in and out of the test section can be established. Such modulation may be necessary for the attainment of general flow stability.

4. Stability Problems

Because of the large volume of air that can be entrained in the flow and the limited volume that can be domed over the test section, any change

in the distribution of the total gas in the system will produce transient pressure conditions in the test section. With slow rates of change, air can be taken from the atmosphere or vented to it without disturbing the general stability of the system. However, if rapid rates of changes are required--as with test models which may suddenly vent or exhaust or models with large pulsing supercavities--the test section and circuit may begin pulsating. Many of these conditions may be tolerable, but others may need to be limited or approached with caution. Operations with the test section at atmospheric pressure and generously vented to the atmosphere will probably prove quite stable. However, with a limited vacuum or compressed air supply to the test section dome, the response time may not be adequate. Under these conditions rapid changes in model gassing may lead to oscillations in the dome pressure.

I. Free Surface Operating Characteristics

If model tests in the ultimate channel facility are to provide reasonable simulations of ship components operating in the infinite ocean, the model should be exposed to a test stream which has a near-planar surface and homogeneous velocity characteristics. In the discussion which follows, these planar qualities are evaluated.

1. Axial Gradients

The free surface axial centerline gradient is shown in Fig. 5 under Item B, relating to test section depth. The values were determined by visual observation of a point gage contacting the free surface. Since the surface was not glassy smooth, but had a very slight flutter, these surface elevations are mean value estimates. While the observations of Fig. 5 relating to the first few feet of the free surface are interesting, it is also important to project these variations for the full length of the test section. The variation in the depth for the prototype tunnel has been estimated from the calculated growth in displacement thickness along the bottom surface. The estimates obtained for the 3 ft test section 25 ft downstream of the lip were for a growth of 0.020 ft at 30 fps and 0.017 ft at 100 fps. The estimates for the alternate test section at 40 ft downstream of the lip are for a growth of 0.032 ft at 30 fps and 0.029 ft at 60 fps.

2. Lateral Gradients

Lateral gradients of the free surface slope were measured in the model at x/D_o values of approximately 2, 4, and 5.6 (see Fig. 5b) for velocities of 30 and 50 fps using a traversed point gage in the manner described in Item 1. The lateral gradients of the slope are shown on an expanded scale. The slope is small in the vicinity of the minimum depth region $(x/D_o \approx 2)$ and increases slightly as the flow progresses downstream. An asymmetry about the centerline is attributed to a mis-alignment of about 15 minutes of angle between the axis of the nozzle and the axis of the test section. This occurred during the assembly of the model channel and demonstrates the need for careful alignment in the prototype.

The surface effects evident in Fig. 5b involve normal boundary layer influences and influences from secondary flows and capillarity at the junction between the window, air, and water. The manner in which these scale up to the prototype is complex and indeterminate. Hence the percentage values of the figure apply to the model, but may or may not apply to the prototype.

3. Smoothness and Stability

Disturbances in the smoothness or steadiness of the test section free surface may be due to either long-time pressure and velocity variations in the total recirculating flow or relatively short-time turbulence fluctuations superimposed on the general flow. The problems of stabilizing the longer-time pressure and velocity variations have already been discussed in sections II-G-4 and II-H-4. Turbulence problems are related mainly to nearby upstream conditions.

Studies by others relative to the breakdown of the surfaces of free jets have shown that internal turbulence conditions in the water lead to the initial roughening of the surface. It is only after the surface has been roughened that air shear conditions begin to contribute significantly to such deterioration. It is therefore important that upstream turbulence generation be minimized. In the present channel design, flow disturbance has been reduced through the use of a small-size tube system in the gas separator and in the honeycomb flow straightener upstream of the contraction. With these a relatively quiet flow enters the large area ratio flow contraction, and if there are no significant adverse pressure gradients on the walls

of the contraction, the discharge from the contraction should possess a low v' velocity component.

Preliminary studies* of this problem employed a circular free jet with a similar 100 to 1 contraction ratio and a low turbulence approach to the contraction. Visual and photographic studies at velocities up to 100 fps indicated that the first few feet of jet surface would be essentially smooth. Downstream of this, increasing rippling and loose spray would occur. However, at a distance of 20 ft, surface disturbances did not rise more than roughly one inch above the mean surface.

Observations in the scale model tunnel with a free surface length of 4 ft and velocities up to 96 fps have shown surface conditions similar to those which existed on the free jet. The four feet of exposed surface did possess small longitudinal surface ripples with heights of the order of 0.01 to 0.02 inch. These grew slowly in the direction of flow. There was, however, no evidence of free spray in the four feet of length available in the nozzle. It is therefore presumed that the break-up further downstream will not materially exceed the one inch observed in the free jet test. It should be noted that in most test studies in the eventual prototype channel only the first few feet of surface will be of major importance.

The above surface stability conditions depend upon absorption of the splash by the splash guard at the downstream end of the test section.

4. Side Boundary Fillets

The description of the slightly rippled free surface given in Item 3 applies only to the central portion of the surface. Where this surface contacts the side walls, deviations from a plane surface are markedly greater. These deviations consist of a fillet sweeping upward from the surface and rising slightly on the side wall. Both the disturbed region on the surface and the rise region on the wall increase in magnitude with increasing downstream distance and are functions of flow speed. The disturbed region diminishes the useful area of the free surface and impairs observations through side wall viewing ports. These disturbances not only fillet the water surface, but in this region also project free spray above the surface and entrain air bubbles below. The approximate dimensions of the obscured and disturbed region, as observed in the model, are shown in Fig. 9. Plotting (not shown) of the tabular values of Fig. 9 indicates that

*Ripken, J.F.; Wetzel, J.M.; and Schiebe, F.R., A Hydrodynamic Feasibility Study for a Large, High-Speed, Variable Pressure, Free Surface Water Test Facility, Memorandum No. M-132, St. Anthony Falls Hydraulic Laboratory, Univ. of Minnesota, April 1972.

the u values increase rapidly in the first 2 ft of X distance and thereafter settle down to a near-linear growth rate. Extrapolation of this linear rate to the prototype test section length of 25 ft yields a u value of 2.0 inches at a velocity of 30 fps and a u value of 4.0 inches at a velocity of 50 fps. The value of u appears to increase rather directly with speed. On the other hand, w appears to increase linearly from $X = 0$, and extrapolated to $X = 25$ ft yields $w = 8.5$ inches for a velocity of 30 fps and $w = 6.25$ inches for a velocity of 50 fps. The value of w changes inversely with the velocity. The mechanisms leading to fillet growth are complex, and the above extrapolations are speculative. They may, however, be some guide for rough estimates of the usable width of the water surface and the height which is viewable through a wall port.

The extent of the disturbed region is believed to depend on capillary effects, turbulence, secondary flow processes, and surface and axial misalignment (for the latter see also Item 2). The first three factors are not controllable, but a high degree of accuracy in alignment is very desirable. In the model, values of only a few thousandths of an inch of window misalignment had marked effects on the disturbance dimensions.

J. Temperature Characteristics

Temperature variations in the test water of a recirculating channel are a consequence of the energy added to the flow by the pump to maintain recirculation against internal frictional resistance. Since viscosity is a significant variable in the mechanics of fluids and is a function of fluid temperature, it is important to have some concept of the range of temperature variation. These variations can be estimated from the input energy of the pump, the channel mass being heated, and the heat loss rates to the exterior. For a given flow condition the first two factors can be calculated fairly easily, but the third item is relatively obscure. However, it is not difficult to measure temperature rise and decline in the model channel and these values may be useful in estimating prototype conditions. Temperature values found in the model channel are therefore shown in Fig. 10.

Experience with other recirculating flow facilities has generally indicated that temperature rise is not a serious problem in most channel operating programs and that expensive heat exchange auxiliaries are therefore not justified.

K. Air Content Characteristics

1. Total Air Control

Experience with water tunnels without a free surface in the test region has shown that the amount of total gas that it is possible to maintain continuously in the tunnel flow can be controlled. This may permit the use of water with a gas content ranging from a high which approximates the saturation for a given test section pressure and temperature to a low which is a small fraction of this value. This control possibility provides for a useful variable in cavitation tunnel operations. The nature of this control possibility, along with other inherent characteristics of an individual tunnel, has much to do with the size of gas nuclei that can be maintained in the flow and thus has a marked effect on the conditions under which cavitation inception or desinence may occur.

In a free surface channel facility with gas separator such as the current design, the water is continually being exposed to substantial amounts of entrained air. Thus wide ranging control over the gas content is not normally possible, and an inherent saturation stability of air content can be expected for any selected set of velocity, pressure, and temperature conditions in the test section. This stability level is not subject to analytical determination, and so limited tests were carried out in the model channel to provide background information. The following three tests were conducted:

1. The channel was operated at a test section speed of 30 fps with the test section vented to the atmosphere until the air content stabilized. At this time a sample was drawn from the test section with a Pitot type sample withdrawing tube. The sample was subjected to a Van Slyke total gas evaluation which yielded a value of 27.6 ppm at a temperature of 79°F. This value is approximately 26 per cent greater than normal saturation at this temperature and pressure condition.

   Similar tests were run at pressures of 1/2 and 2 atmospheres absolute. The values were 16.4 ppm at 81°F at 1/2 atmosphere and 46.2 ppm at 81.5°F at 2 atmospheres. These values are respectively 158 and 106 per cent of normal saturation for these conditions.

2. The channel was operated until air content stabilized at a test section speed of 30 fps and under a pressure of 1/2 atmosphere. Gases collected in the test section dome were extracted by vacuum. Upon the achievement of stability, the test section pressure was raised to atmospheric. The velocity of 30 fps was continued. At ten-minute intervals following the raising of the pressure, water samples were again withdrawn from the test section. These samples were subjected to Van Slyke total gas evaluation. The resulting time progression is plotted in Fig. 11.

3. Test No. 2 was repeated using an initial test section pressure of 2 atmospheres rather than 1/2 atmosphere.

Comparative study of the values of the three tests in Fig. 11 indicates the following:

1. The channel inherently stabilizes the total gas content to a value significantly greater than the standard saturation value for the pressure and temperature conditions prevailing in the test section. This is due to the fact that throughout most of the channel recirculating loop, the water is exposed to large quantities of free air at pressures considerably greater than that in the test section.

2. Stabilization takes place in less than 100 minutes whether the water is markedly undersaturated or oversaturated at the beginning of operations. Note that the initial rate of change of air content is very great when the air content is significantly greater or less than the stabilized value. Hence the stabilization time can be reduced greatly by "overcorrecting" the pressure for a short period of time when changing test conditions to force the air content to reach the desired level more rapidly.

2. Characteristics of Entering Free Air

Small air bubbles in the test water of a cavitation test facility are usually essential for the proper simulation of cavitation. Extensive studies conducted for the Navy at the St. Anthony Falls Hydraulic Laboratory have established that under the low pressure conditions in most tunnel tests, meaningful inception cavitation data require free air nuclei in minimum concentrations of about 2 to 10 parts per million by volume in diameters

ranging from about 0.02 to 0.15 mm. Such bubbles will readily serve as nuclei for the rapid growth of vapor cavities encountered in limited or transient cavitation without significantly hampering visual or photographic observation of test subjects or impairing the dynamic performance characteristics of either the models or the facility. For studies of more fully developed or supercavitation, small air nuclei are less important, but excessive air continues to impair proper performance and observation.

The free air characteristics of the proposed channel design in the model facility were evaluated in two steps. First, the bare channel was operated at progressively increasing test section speeds ranging from 10 to 70 fps and with the test section pressure varying from 0.2 to 2.0 atmospheres absolute. During these tests the water passing through the test section was observed under stroboscope light and flash photographs were taken to characterize the optical impairment caused by the bubbles. Figure 12(d) is a photograph taken through 7-1/2 inches of water under the worst conditions observed. The general conclusions are that bubbles inherent in the channel action caused some optical impairment as indicated by the overall lightening of the background. Some of what appear to be bubbles in Fig. 12(d) are actually blisters in the painted background. These blisters can be seen in the "no flow" photograph, Fig. 12(c).

The second step was similar to the first except that air equivalent to the maximum specified prototype value (0.4 per cent) was injected at the downstream end of the test section. The photos in Fig. 12(b) were taken under the worst conditions observed with this injection. The general conclusions regarding this test are that the injected air causes no significant optical impairment.

III. CONTRACTION AND NOZZLE

A. Flow and Dimensional Requirements

The contraction is provided in the flow circuit to accelerate the low speeds required in the air separator to the high speeds required in the test section (1 fps for low with 100 fps for high). The prime objective is to accomplish the acceleration in such a way that in the test section the velocity uniformity is high and the turbulence level low. Velocity uniformity is largely controlled by an interplay of velocity, pressure, and energy conditions in the contraction and improves with an increase in the contraction ratio (entrance area : exit area). Since the contraction ratio for the proposed channel is exceptionally large (approximately 100 to 1), flow will be unusually uniform if the contraction length is sufficient to permit full contraction to take place. The proposed contraction is shown in Fig. 13. The axes of the approach flow and the discharge flow have been offset vertically by the 12 ft 7 in. dimension shown. This was done because

a. More favorable pressure conditions can be maintained between the air separator dome and the test section dome.

b. The length of the roof boundary is thus minimized.

c. Less water is drained in unwatering the test section.

All four corners of the nozzle have been provided with generous fillets in order to minimize the generation of longitudinal vortices that would otherwise occur with sharp corners. These fillets are large at the nozzle entrance and diminish with progress downstream. The upper fillets progress to zero radius at the downstream end of the nozzle.

It should be noted that the system employed does not complete the contraction of the top of the flow within its boundaries, but depends on additional free surface contraction after the flow leaves the closed circuit. Thus it is quite different from conventional water tunnel contraction systems in the following respects:

a. To allow complete contraction of the flow, the solid boundaries must usually be quite long, and a substantial amount of boundary layer growth occurs due to the high velocities present. This boundary layer growth is detrimental, because it consumes energy and diminishes the effective area of the test flow. In the free surface channel the downstream part of the roof is replaced

by an air boundary. The flow then contracts and the velocity profile normalizes in the test section, where air shear is modest (see section II-G-6). This requires increased housing length for the test section. The amount of increase necessary is discussed in section II-C.

b. If a solid boundary is employed for the full length of a contraction, the downstream portion usually involves a reversal of curvature in order for the flow to exit parallel to the axis. If this boundary reversal is not designed and constructed properly, adverse boundary pressure gradients may develop. These can generate separation eddies which may be seriously detrimental to stability in the exiting flow. This would particularly disturb a free surface flow. Removing the downstream portion of the solid boundary also removes the conditions which cause flow separation.

For the proposed prototype channel the dimensions of the contraction cone and nozzle are as detailed in Fig. 13. The major area and shape changes of the contraction occur in a component referred to in Fig. 13 as the "shape transition." In this large component the cross-sectional shape changes from circular, with a 34 ft diameter, at the upstream end to rectangular with dimensions of 9 ft 7.2 in. by 8 ft 0 in. at the filleted downstream end. The geometric form of this component has been kept relatively simple to permit fabrication by weld-up of structural plates. The plates would be made of rounded brake-bent corner pieces and flat triangular gore pieces.

The lesser, but more refined and critical area and shape changes of the contraction occur in a component referred to as the "nozzle" in Fig. 13. In this smaller component the shape changes are less pronounced than in the shape transition, but the complexity of change is markedly greater, and fabrication of the nozzle is believed to require casting. The dimensions of the nozzle component, based on joining tangential end lines with simple mathematical curves, are given in the table of Fig. 13. These dimensions define the curvature of the roof, floor, and side walls and the joining fillet radii.

The curve of the roof joins a horizontal tangent line at the entrance to a tangent at 30° with the horizontal at the exit. The connecting curve

is given by an equation of the form $Y = AX^3$ with the origin at the upstream end.

The curve of the bottom joins a tangent line of 38° 51' slope at the entrance to a horizontal tangent at the exit. The connecting curve is a portion of a simple ellipse. The side wall curves join a tangent line which is at an angle of 23° 17' with the test section axis to a tangent which is parallel to the test section axis. The connecting curve is a portion of a simple ellipse.

The geometric form and mechanical finish of the extreme downstream end of the roof curve of the nozzle is a critical factor in the smoothness and stability of the water surface as it enters the test section. It is recommended that the last 2 inches of this curve be a removable straight tangent "lip block" with a slope of 30° with the horizontal. A removable block is considered desirable because

a. Unlike the nozzle casting, which may not be subject to machine finishing, the lip block can be machined and finished with a high degree of quality control.

b. In the event of damage to the delicate knife-edged lip, it can be replaced without major field efforts.

c. The lip can be replaced by other geometric forms to achieve other types of water surfaces if future requirements dictate.

It should be noted that while a 2 inch long block has been included in the total dimensions of Fig. 13, the model studies employed a straight 30° lip with an axial length of only 1/8 inch. The latter figure is the basis for the last X value in the table of Fig. 13.

B. Surface Finish

Achievement of low turbulence flow in the water surface in the test section requires that the roughness and waviness of the boundary surface of the nozzle be minimal. This is true in the high velocity regions at the downstream end of the nozzle and especially true for the surfaces of the roof. As the surfaces extend farther upstream, the surface quality standards can be relaxed, but adherence to correct shape remains important. It is practical to hand grind or machine finish the surface contours of the small nozzle, but initial surface deficiencies will be more difficult to correct in the formed structural plates that will constitute the shape

transition. If care is taken in aligning joints and welding, finishing will be necessary only at the welds and at the break plane at the downstream end of the shape transition. Values for the finishes of these surfaces are given in Fig. 39.

C. Auxiliary Features

1. Air Drainage

The gas separator removes extraneous air from the recirculating water. It does this fairly effectively, but not completely. In consequence, some coalescence and gravitational concentration of part of the remaining free gas may occur in other parts of the channel circuit when velocities are low. The large cross section near the upstream end of the contraction is of this nature and may promote a modest collection of free air along the roof boundary. It is suggested that a collection slot or perforated area be provided at the crown of the roof for air collection and removal. This collection point should be located just upstream of the break plane between the shape transition and the nozzle. The surface at the collection point should be porous or permeable, but without significant misalignment or openings exceeding 1/8 inch.

2. Break Plane

It is suggested that a physical break plane or flanged joint be provided between the shape transition and the nozzle. This is a logical junction point for the widely differing fabricating materials of these components. It should be located where velocities are moderate and modest surface irregularities will not be as detrimental to flow as they would at locations farther downstream.

The break plane is essential as an upstream terminus for the alternate and removable test section units depicted in Fig. 3. It also provides a sizable access opening for initial installation and later possible maintenance of the elbow guide vanes, diffuser screens, gas separators, and flow straightener.

3. Piezometric Tap for Speed Indication

As is noted in section II-F-6, a piezometric tap should be provided just upstream of the shape transition. This tap will contribute to the evaluation of the pressure differential across the total contraction and to subsequent evaluation of the test section velocity.

D. Velocity Characteristics

Although the very important velocity characteristics of the test section, as described in section II-G, are formed in the contraction, no direct internal velocity measurements were made in the model channel study. However, the very important boundary velocity conditions in the nozzle were detected indirectly through the boundary pressure measurements which are discussed in the following section.

E. Pressure Characteristics

As is stated in section A above, variations in the pressure along the boundaries of the contraction are important, because the presence of adverse pressure gradients indicates the possibility of separation eddy generation. To establish the nature of the boundary pressure changes, the nozzle of the model channel was fitted with eleven 1/16 inch diameter piezometric taps along the centerlines of the roof, the bottom, and one side wall.

Subsequent runs at test section velocities of 20 and 30 fps established the pressure data which are shown graphically in Fig. 14. In this normalized plotting the local pressures are related to the pressure at the upstream end of the contraction and to the velocity head in the test section to provide a dimensionless pressure coefficient. The following points relate to the data offered in Fig. 14:

1. Only the data for the test at 30 fps are shown. The 20 fps data were virtually identical and would only have complicated the plotting.

2. The data for all three boundaries appear to form smooth curves without irregularities or potential for separation effects.

3. The low pressure coefficients for the roof taps suggest that the velocity along the roof remains low until just before the flow reaches the contraction lip, where full test section velocity is achieved. Rapid acceleration to a pressure coefficient of unity must occur in a very short distance with minimal opportunity for boundary layer growth. This is supported by the observed boundary thickness shown in Fig. 7.

4. For flow along the bottom, test section velocity is presumed to be achieved only when the contraction has completed itself as shown in Fig. 4. The pressure data of Fig. 14 have been extrapolated at the right-hand side to reflect this possibility.

5. For flow along the side walls, test section velocity has been presumed to be achieved midway between the end of the nozzle and the end of the surface contraction. The curve has been extended beyond the actual data to reflect this possibility.

IV. SKIMMER AND TRANSITION SYSTEM

The skimmer system is an assembly of sub-components whose primary function is to re-introduce the free surface flow of the test section back into the closed conduit loop which recirculates the flow to the test section. The re-introduction process must not cause degradation of the flow quality requirements discussed in section I. In order for stability to be maintained, the conduit must be essentially full of water and without a discrete free surface. This was achieved using a sharp-edged roof plate which is designated as the skimmer lip, component 1 in Fig. 15. The lip which was adjustable vertically, was positioned so that the flow passing beneath it no longer possessed a discrete free surface. The flow skimmed off above the lip was a two-phase flow containing a substantial percentage of free air. The objective was to set the lip as high as possible in order to minimize the amount of skimmed flow which had to be processed and returned to the flow being recirculated in the closed conduit. On the other hand, the lip had to be low enough that a free surface would not occur in the main diffuser, since such an occurrence would cause reattachment or jump type flow in the region of the first elbow, and a violent and unstable flow process would develop. Because a most favorable lip setting depends on a number of test section conditions which may vary with different test studies, it was considered unlikely that one setting condition would best serve all needs. Accordingly, the lip was made adjustable to about 5 per cent above or below the normal test section depth.

The various sub-components of the proposed prototype skimmer, assembled, are shown in Fig. 15 with their dimensions. The system employed in the model study to convey the skimmed water from the skimmer back into the conduit is shown in Fig. 16. In the write-up which follows, the rationale, functional operation, fabrication, and selected dimensions of the significant elements of Figs. 15 and 16 will be discussed.

A. Housing Chamber for the Skimmer-Transition

The flow passage into the chamber has the same 3 ft width as the downstream end of the test section and continues to be 3 ft wide for the first 6 ft of chamber length. The transition curve between the parallel walls of the test section and the $3^{\circ}\ 38'$ flared walls of the diffuser should take up the next 3 ft. The transition curve is a simple parabola with a

beginning which should be tangent to the test section wall and a terminus which should be tangent to the diffuser wall. The arrangement is shown in the Sectional Elevation and Section A-A portions of Fig. 15.

The height of the chamber should accommodate the 3 ft deep test stream and the 7 ft high air dome discussed previously with regard to the test section. The main reason for the high dome in this chamber is that it must house the large skimmer. This is an assembly of components 1, 2, 3, 4, 5, and 7 as shown in Fig. 15. The roof of the chamber should support the skimmer adjusting mechanism (component 5) at a high level and should drop to a lower level in the downstream end. The latter will permit the jack screw (component 6) and the viewing window (component 13) to be placed closer to the skimmer.

A break plane (shown as component 16) or flanged joint should be provided to permit insertion of the prefabricated splash guard (component 15), skimmer (component 2), and flexible roof (component 9) during assembly.

B. Adjustable Skimmer

The adjustable skimmer is a large cylindrical sub-assembly whose key part is the knife-edged skimmer lip (component 1) which spans the entire width of the flow channel. In the prototype this lip is to form the lower side of a 4.75 inch high flow passage which will serve as the entrance for the skimmed flow passing into the skimmer housing (component 2). The skimmed flow is to be carried upward and to the sides by the outer wall of the skimmer housing and by inner partitions, a flue tube (component 3), and a chimney tube (component 4). The skimmed flow is to discharge from both ends of the skimmer housing (component 2) into the separation chambers (component 17) on each side of the channel. Here a substantial amount of the air in the skimmed flow is to separate from the water. The water is to drain from the bottom of the separators through attached discharge pipes (component 12) with the water roughly following the route marked by the dotted line. The separated air is to be free to return to the test section by way of the air flue (component 3) and the air chimney (component 4) following the route marked by the dashed line. Air undoubtedly will also return in substantial quantity via the top of the initial skimmer entrance.

Original planning for component 17 was based on the assumption that the skimmed flow would be discharged from the skimmer and would proceed with

a definite vortexing action around the periphery of the cylindrical chamber 17. The vortexing flow would be discharged from chamber 17 via discharge pipe 12, which is tangential to the cylindrical chamber. The vortex action was presumed to promote both separation of the air and water and flow into discharge pipe 12 with some remaining kinetic energy. Observations in the model did not show such vortexing action. Thus there is no hydraulic reason to adhere to a cylindrical separation chamber or a tangential location for the discharge pipe in a prototype design.

In the model studies the skimmer lip (component 1) and the flexible roof (component 9) were welded into one rugged stainless steel sub-assembly.

The cylindrical skimmer housing (component 2) was fitted with integrally welded large end flanges (component 7), and the total length of the assembly was machined to a snug sliding fit between the walls of the housing chamber. The fit enabled the entire skimmer assembly to be freely adjusted up or down for vertical positioning with major leakage across the flanges avoided. The flanges were made large enough to cover the fixed holes through the chamber wall for all adjustment positions. The edges of the flanges were faired to a small thickness for those portions contacting the flow as it entered the lip.

The skimmer assembly was raised and lowered by a lifting stem attached to the top of the air chimney (component 4). The lifting stem was activated by a hydraulic oil cylinder located above the housing chamber. The pressurized oil was supplied and controlled by a small packaged motor, pump, and valve assembly activated by an electrical push-button for up or down motion. The skimmer position was read out by a dial micrometer attached to the upper end of the hydraulic cylinder. A total travel of ± 0.5 inches was found satisfactory for all operations conducted in the test model, and hence a travel of ± 2.5 inches is recommended for the prototype. Most of the dimensions of the skimmer design of Fig. 15 are not considered highly critical.

Operations with the foregoing skimmer design in the model channel have shown good performance with no serious problems (see separate discussion dealing with difficulties in the skimmed flow pump return circuit). It was originally anticipated that under high speed cavitation conditions the skimmer lip would generate substantial large cavities with resulting instability and high noise levels. Actual observations through the viewing window below the skimmer lip have shown only small cavities and no significant

signs of instabilities or appreciable noise. The continuous presence of substantial quantities of free air in the flow in the vicinity of the lip appears to produce acceptable working conditions even though some cavitation seems to be present.

Although very substantial skimming can be accomplished with the system described, deep skimming does not appear essential to achieving good test section flow. This fact can be attributed to the large air separating capacity of the main separator, which reduces the need for the skimmer to skim and de-aerate.

C. Flexible Roof

The roof of the conduit proceeding downstream from the skimmer lip becomes part of the fixed roof of the main diffuser. Since this roof must be rigidly fixed at its downstream end and have vertically adjustable support at its upstream end, some part of it must be flexible. In the model studies the flexible roof was component 9 of Fig. 15 and had a length given by dimension 10. This component was also made to serve as the transition curve between the horizontal free surface and the main diffuser roof, which was at a slope of 3° 30' with the horizontal. Accordingly, the end supports of the flexible roof confined the ends to these slopes.

In the model the roof was made from a 1/2 inch thick plate of annealed T-16 stainless steel. Lateral grooves of 1/4 inch width, 3/8 inch depth, and 1/2 inch spacing were milled across the width of the plate. The resulting plate had sufficient elasticity to flex without permanent deformation, but was presumed to have enough mass and lateral stiffness to remain dynamically stable. The flexible roof was originally bent (permanently deformed) to the shape of the roof transition curve for the neutral position of the skimmer lip.

The edges of the flexible roof were contoured to fit the shape of the side walls, including both the straight and the transition curve portions. This fit was made for free vertical motion of the roof, but was kept as tight as was practical to minimize flow leakage.

During operations the flexible roof was maintained in a state of modest tension by suitable use of two jack screws (component 6). The exact shape of the roof under these conditions is not known, but the overall operation seemed quite satisfactory.

During the limited test program with the model channel there was no evidence to refute the worth of the above described design concepts. However, because of the large amount of energy available in the prototype stream (16,000 HP) and the large forces that could be generated by a malfunction or detachment of moving parts, the prototype flexible roof should be designed very conservatively.

D. Boundary Transition Curves

The boundary transition curves are provided as a means of gradually changing from the axial direction or tangents of the test section boundaries to the flared direction or tangents of the boundaries of the main diffuser. Prior experience has shown that rapid changes of direction will produce low negative local pressure values and boundary cavitation. This can be prevented if a low rate of change of boundary pressure is used. In the proposed design a conservative approach was employed by starting the flow expansion only on the roof and floor (in the model, the curvature of the floor was initiated upstream of that on the roof; that is not advocated for the prototype as shown in Fig. 15). It is recommended that these transition curves have a prototype length of 6 ft with a gradual-starting parabolic curve (components 8 and 9 in Fig. 15).

Transitions on the side walls were made only half the length of those on the roof and floor, but with their terminus in the same plane. Because their origins would be in a region of slightly greater pressure than those of the roof and floor, the danger of cavitation was considered less. Observations in the model channel have not disclosed difficulties with this design.

E. Vortex Generators

The vortex generators are located within the confines of the skimmer-transition system, but their flow function is more critical to the main diffuser located just downstream. They are, therefore, discussed along with the main diffuser in section V.

F. Surface Finish

The surface finish requirements for the skimmer-transition are slightly relaxed compared to those for the test section (see section II-E); they are tabulated in Fig. 39.

G. Auxiliary Features

1. Splash Guard

The splash guard shown as component 15 in Fig. 15 is located in the skimmer transition housing chamber, but is functionally related more closely to the test section. Therefore it is described in section II-F-7.

2. Visual Access

In the model studies four viewing windows were provided to permit visual observation of interior conditions. They were located in the floor below the skimmer lip, at the top downstream end of the housing chamber, and at both ends of the separator chambers. These windows proved to be of considerable value in observations of operating conditions in the model study, and comparable provisions are recommended for the prototype.

H. Skimmed Flow Return System

In order to maintain continuity and stability in the recirculating flow of the channel, it is necessary to return all the flow skimmed from the surface of the test section to the main stream. The return of the free air has been described in section IV-B. The return of the water, however, is somewhat more complicated and involves an external pump flow circuit. The model study version of this flow circuit is shown in Fig. 16, and its function and operation are treated in the discussion which follows.

1. Return Piping Circuit

The nature of the skimmed flow and the operations of the skimmer provide a discharge flow from the skimmer which possesses the test section static pressure and a low level of kinetic energy. If this secondary flow is to be returned to the main recirculating flow stream, it should be returned at a point where it will not detrimentally affect the main flow and where a minimal boost in energy head is needed. The first requirement suggests that re-introduction should avoid (a) the sensitive high-speed flow of the diffuser, (b) the complicated high-speed flow of the first elbow, and (c) the sensitive inflow side of the pump. The second requirement establishes preference for introducing the flow somewhere upstream of the main recirculating pump. A flow route proceeding from point 1 to point 3 of Fig. 16 was therefore selected as a possibly favorable compromise.

The objective of the return flow circuit is to continuously and steadily provide for drainage and return of the water being skimmed from the free surface of the test section. The circuit must provide good stability of the total system for either steady-state or slowly changing conditions in the test section. In the first pass, it was not considered advisable to strive for the high response, high capacity system that might be needed to match high rates of change in the skimmer flow.

In the oversimplified system used in the model studies as shown in Fig. 16, three key components were provided: a reservoir (component 10), a pump (component 4), and a control valve (component 6). The reservoir was a chamber in which a free surface of limited extent was provided for control purposes. When arranged as shown in Fig. 16, the reservoir was intended to provide constant gravity drainage of the flow skimmed from the test section regardless of small controlled variations in the skimmer pump flow. Any variations in pumped flow were accommodated by small fluctuations in the height of the free surface (area ≈ 6 sq ft) which the valve operator could observe and make valve adjustments to stabilize. The reservoir was also provided with baffles allowing the pump to withdraw water from which the air had been largely eliminated by separation at the free surface (until this air was removed the centrifugal pump performed very erratically because of air binding). The separated air was returned to the test section through a separate vent pipe. The free surface reservoir was placed as high in the system as possible to provide a maximum net positive suction head on the skimmer pump for suppression of cavitation.

Progressive work with this system has indicated that in its present form, flow rate changes at the skimmer must be very slow if the stability of the skimmed flow is to be maintained.

The sizing of the circuit piping and the booster pump was directed toward skimming 5 per cent of the test section depth or assuming 5 per cent of the test section discharge at maximum speed.

While test section conditions were being changed in the model studies, the skimmer was continuously monitored manually and proved to be extremely sensitive to changes which were not made very slowly. Maladjustments in skimmer control resulted in flooding of the test section and loss of the test. These sensitive operating conditions would not be tolerable in the prototype, and a fully automated system is suggested. The following

improvements in the system of Fig. 16 are believed to be essential for controlled and stable operation:

a. The diameter of the free surface reservoir should be large enough that the change in level of the free surface can be followed by a sensor which activates the pump (component 4) or the control valve (component 6) shown in Fig. 16. This signal should regulate the flow discharge so as to maintain the operating range of the free surface level within selected limits controllable by the sensor.

b. The pump should be of such a type, or be so operated, that significant cavitation does not occur and modest levels of free air do not "air bind" it. A fixed speed pump may prove satisfactory if other controls are adequate. However, if high rates of change are to be accommodated, pump speed variation may be a necessary part of an automated system.

c. The discharge control valve should have a capacity and time of response adequate to control the flow sufficiently to satisfy the command of the free surface sensor.

d. Rates of change in return flow discharge should be such that de-stabilizing pressure waves are not imposed on the main flow circuit.

e. It was originally thought that the region downstream of the skimmer housing and above the flexible roof would flood with water from leakage around the edges of the flexible roof. This water would then either leak into the interior of the skimmer housing, and be bled off, or well up and over the top of the skimmer with drainage into the test section. Later high-speed model tests established that under some operating conditions the flow over the top of the skimmer was substantial and that when it dropped on the surface of the high-speed flow, significant splash was driven upstream. This splash occurred at too low a level to be intercepted by the splash guard. In order to minimize this splash effect and also the destabilizing conditions at the skimmer lip, it was decided to drain off this leakage water downstream of the skimmer housing and prevent its overflowing the housing. This was accomplished in the model

study by attaching a 2 inch drain pipe to the side wall of the skimmer chamber. This pipe was carried down and connected to the reservoir of Fig. 16 to allow gravity drainage. This flow was not metered for quantity, but it was assumed that an 8 inch pipe would suffice in the prototype.

2. Return Flow Discharge Diffuser

The skimmed flow, which may amount to as much as about 5 per cent of the main flow, should be returned to the main flow in a manner which will not abnormally disturb the main flow. This has been discussed briefly in section IV-H-1, which explains why the skimmed flow was returned to the main flow at point 3 in Fig. 16. The details of the diffuser itself are discussed in section VII in relation to the downcomer.

3. Skimmer Booster Pump

This pump is required to process a flow which may range up to 5 per cent of the main flow (≈ 45 cfs in the prototype). The effective head against which the pump must work is essentially the difference between the test section pressure (presumed to exist at the free surface of the reservoir) and the pressure in the downcomer conduit at point 3 in Fig. 16. This pressure difference varies with test section velocity; for pump selection purposes it is estimated that this effective pump head should be about 0.9 times the test section velocity head. The total pump head will be this effective head plus any losses incurred in the eventual prototype skimmer circuit. A centrifugal type pump will generally fulfill these requirements most simply, and if it is positioned low with respect to the test section, cavitation can be prevented.

Adjusting the pump to meet the variable demands of the skimmer system requires either a throttling of the discharge of a constant speed pump or provision of a variable speed pump. In the simplified model set-up shown in Fig. 16, a valve provided for control of a fixed speed pump. With careful monitoring this system worked fairly well in the model study, but it is not advocated for the prototype. A system using a single large, variable-speed pump or a complex of several smaller pumps, one of which is a variable-speed pump, is recommended. The latter type of system is commonly used in water supply practice and provides good energy economy with wide ranging flow flexibility. Such a system of pumps controlled by a level sensor in the

reservoir might provide the necessary control without valving. The more sophisticated system has not been investigated in the current study.

4. Flow Meter

A constriction type flow meter (component 5) was provided in the model studies together with a meter in the purge circuit to establish the rate at which water was skimmed. These meters were not used in the model, and there seems to be no reason to provide a discharge meter in the prototype circuit.

5. Control Valve

As mentioned in sections IV-H-1 and -3, the control valve in the model study allowed adjustment of the pumping rate to match the rate at which skimming was taking place. In the manually monitored procedures employed in the model, some problems were encountered in maintaining a rapid enough response by the flow to the changes in the valve and pump to prevent flooding of the test section. Whether a valve will be necessary in the prototype depends on the controlled sensing of the water level stage in the reservoir and the accompanying response that can be provided by a variable speed pump.

In initial model studies the responses of the pump and control valve were materially aided by the addition of the purge circuit shown as component 8 in Fig. 16. Subsequent addition of the reservoir shown as component 10 eliminated the need for the purge circuit, and it is not advocated for the prototype control system.

V. MAIN DIFFUSER

A. General Considerations

The principal objective in designing the main diffuser is to assure the conversion back into static head of as much of the test section dynamic energy as practical. This is important to minimize both the operating energy input requirements and the circuit destabilizing forces that accompany high energy losses. The most notable requirement in the latter regard is the prevention of major boundary layer separation and the accompanying flow instability.

Diffusers are most commonly designed as simple area expansions. A large fund of analytical and experimental data is available regarding the designing of diffusers of circular cross section and large aspect ratio, but little is available on square sections such as that needed in this case. A study of the literature indicates that the following considerations are important regardless of the specific geometric form:

1. Pressure recovery requires that the expanding flow work against an adverse pressure gradient.

2. Boundary layer shear concepts recognize that the flow velocity approaches zero as the boundary is approached.

3. Flow elements nearing zero velocity or kinetic energy must move upstream in an adverse pressure gradient unless existing momentum exchange mechanisms (turbulence) are sufficient to maintain forward movement.

4. Upstream boundary flow may trigger major separation of the principal flow and must be inhibited.

5. Effective inhibition of separation is dependent on a balance between the available turbulence mechanism and the geometric conditions which establish the gradient of adverse pressure.

6. In a specific case, the turbulence mechanism available to combat separation is the natural turbulence of the upstream boundary layer along with random disturbances from other upstream sources.

7. The occurrence of separation also depends on the length of the expansion. Diffusers inherently amplify the peakedness or

asymmetry of entering velocity distributions, and the ability to suppress separation accordingly deteriorates with length.

8. A combination of diffuser dimensions and input boundary layer conditions which has not been thoroughly vindicated by previous investigations can be suspected of contributing to separation and should be experimentally simulated and studied before acceptance.

B. Selected Dimensions

The dimensions of the proposed main diffuser are shown in Fig. 17. The dimensions are fixed mainly by the entrance requirements, the exit requirements, and the length. The entrance dimensions in this case are determined by considerations relative to the upstream skimmer-transition; these are treated in section IV. Similarly, the exit requirements are fixed by the desired performance conditions in the downstream elbow, which are treated in section VI.

The length of the diffuser is arbitrary and should be a minimum consistent with achieving a non-separating flow. Diffuser experience indicates that a total internal angle of 7° as shown in Fig. 17 produces a rate of area and pressure change which is recognized as stable and conservative for the turbulence mechanisms that are usually available. The diffuser length is thus fixed by this angular selection. It should be noted that, for a number of reasons, the model diffuser length is relatively shorter than (about 83 per cent as long as) that proposed for the prototype.

C. Turbulence Mechanism

While the foregoing selection of the 7° diffuser angle appeared conservative based on prior art, early studies of the velocity profile at the downstream end of the diffuser disclosed major separation (see Fig. 18a). The separation occurred from the floor and gave essentially zero flow in the lower 1/4 of the cross section. A study of the probable causes suggests the following:

1. In the model the transition curve between the floor of the test section and the floor of the diffuser began 7-1/2 inches upstream of the beginning of the roof transition. This inadvertent geometric selection involves pressure conditions which could promote separation in the floor boundary layer.

2. As shown in the velocity profiles of Fig. 7, the boundary layer on the test section floor was much thicker than the boundary layer in the free surface. This initial asymmetry may contribute to the separation.

3. As discussed in sections II-G and II-H, the general level of turbulence in the core of the test section flow is extremely low because of the very high contraction area ratio employed. This provides very little external stimulus to momentum exchange at the boundary. Moreover, the large contraction ratio is designed to generate a minimal boundary layer thickness. In consequence, far lower than normal values of turbulence and momentum exchange can be expected for the flow entering the diffuser in this case.

All the above potential sources of flow separation could possibly be corrected for by an artificial increase in the mixing or exchange at some point downstream of the test section, but upstream of the diffuser. This possibility has been studied using vortex generators as described in the following section.

D. Vortex Generators

Various forms of devices have been used in the past to generate longitudinal vortices which appear to provide a desired mixing in a simple manner. On the basis of an illuminating design study*, a vortex generator described as a triangular plow was employed to correct for the observed model flow separation. In the initial model tests a single row of two model plows was used. This choice followed the findings of Schubauer and Spangenberg* that a few large generators in a single row generally produced better results than multiple rows or greater numbers of smaller generators in a row. In the model tests the two plows were made 1/2 inch high, 1-1/2 inches long, and 1 inch wide. This arrangement yielded the test velocity profiles shown in Figs. 18a and 18b. The profiles in Fig. 18b showed good lateral symmetry and acceptable velocities in the vicinity of the side walls. The vertical profile was materially changed by the vortex generators, showing small but positive velocities near the floor, but still some asymmetry and

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*Schubauer, G. B. and Spangenberg, W. G., "Forced Mixing in Boundary Layers," Journal of Fluid Mechanics, Vol. 8, Part 1, May 1960.

considerable peaking. In order to improve the latter conditions, additional model tests were conducted with plows 50 per cent larger. These tests, as is also shown in Fig. 18a, improved the floor velocity, asymmetry, and peakedness in the vertical velocity profile, but caused major separation from the left wall as shown in Fig. 18b. It appeared that the modest level of mixing provided by the smaller plows was a better overall solution than that provided by the larger plows, since they essentially eliminated separation while taking a smaller drag toll.

In the model studies the vortex generators were bolted to the viewing window as shown in Fig. 15. In this position they were clearly visible, and, as anticipated, under low pressure conditions they showed very visible and stable cavitating cores along the axes of the four longitudinal vortices that were generated.

Under some combinations of pressure and velocity, considerable noise could be heard in the diffuser. The noisy region was not visible, but the noise was presumed to be caused by the collapse of the trailing end of the vortex cavity as the vortex moved into the rising pressure field of the diffuser. It is believed that the noise could be readily damped by supplying a small quantity of air flow to the topside of the vortex generators.

The possibility remained that the entire diffuser separation problem could be satisfactorily solved by moving the origin of the transition in the model to a downstream position beneath the origin of the roof transition. Unfortunately, time did not permit this revision, and so the smaller vortex generators were used in all model operations. Thus it is not known whether the vortex generators shown in prototype size in Fig. 15 will be necessary.

In addition to the possible improvements to be gained by moving the origin of the floor transition curve in the prototype, it is recognized that there will be some flow changes due to boundary layer scale-up. These changes will detract from the accuracy of the estimates of probable prototype diffuser performance, but the eventual performance could in any case be readily remedied by judicious trial use of vortex generators. In view of the significant drag contributions from the generators, it is not recommended that they be used until their necessity in the prototype has been established. To this end it is suggested that the prototype diffuser provide centerline access for a velocity probe at the downstream ends of all four boundaries. These could be short, small-diameter probes for simply

determining whether positive velocities existed near all boundaries. In the event of velocity deficiencies, vortex generators could be bolted or welded to the appropriate boundary in the general manner shown in Fig. 15. The velocity profiles shown in Fig. 18 relate to test section velocities of approximately 30 and 50 fps.

E. Energy Recovery

The relative energy recovery of the diffuser was approximated for a low skimming rate by appropriately evaluating the energy flux per pound of flow at the entrance and exit of the diffuser. These values indicate that the diffuser is reasonably efficient. More specific data are given in the head loss analysis of section VIII.

F. Surface Finish

The surface finish requirements for the diffuser are relatively high in the high velocity regions of the upstream end and diminish toward the downstream end. Quantitative values are tabulated in Fig. 39.

VI. FIRST ELBOW

A. General Considerations

The flow turning elbows of a recirculating test loop are normally employed to provide 360° of controlled turning action. For practical use in a water facility the important requirements of an elbow design are energy losses which are not excessive, reasonably compact size, a minimum of detrimental contributions to the discharge flow quality (in the form of velocity profile abnormalities, large scale turbulence, flow instability, etc.), freedom from cavitation, and a form suitable for practical fabrication. A long history of study and development in wind and water tunnel practice has led to the current satisfactory employment of the vaned 90° miter elbow.

For the proposed facility the first elbow is being treated separately from the other three because of its different shape and higher operating velocity. The high velocities in this elbow are the result of foreshortening the length of the main diffuser to improve the diffuser's stability. The higher velocities impose heavier hydrodynamic loads on the turning vanes, and because of the low pressures accompanying the high velocities, cavitation is possible. Due to the heavy vane loading in this elbow it was considered desirable to use a thickened profile rather than a bent flat plate.

The square shape of the first elbow follows from the square shape of the preceding diffuser exit. Since it is considered unwise to expand the flow in the turning process, the selected design has the same cross-sectional dimensions upstream and downstream of the turning vanes.

B. Selected Dimensions

The 8 ft size of the elbow cross section as shown in Fig. 19 is a minimum based on estimates of the largest tolerable velocity that might be achieved without vane cavitation. The cavitation limit is in turn based on earlier studies conducted at St. Anthony Falls* in which it was established that the pressure distribution on the vane surface meant a critical value of 2.25 for the cavitation Sigma based on the local mean velocity.

The shape, orientation, and spacing of the vanes were taken directly from the earlier findings*, but the absolute size and number of the vanes

*Ripken, John F., "Vaned Elbow Studies," Ch. 5 of Design Studies for a Closed-Jet Water Tunnel, Technical Paper No. 9-B, St. Anthony Falls Hydraulic Laboratory, Univ. of Minnesota, 1951.

are arbitrary choices bounded by the fact that a large number of vanes would lead to small and weak cross sections for the given span of 8 ft, while a small number of vanes would lead to a large and stiff structural section, but also to a coarse pattern of wakes in the flow with large flow end effects or secondary flows between vanes. In this case 9 vanes and 10 vane gaps were decided upon. The resulting dimensions, obtained by multiplying model values by scale ratios and rounding off, are shown in Fig. 19.

C. Auxiliary Physical Features

1. Visual Access

Viewing windows in the elbow are not necessary for normal operations, but might prove desirable for monitoring special tests. Two windows positioned as shown in Fig. 19 were quite useful in the model study.

2. Air Vent

Because the top of the elbow is above the test section, air will collect at this high point when the tunnel is filled with water. For stability of operation, all collected gas pockets should be eliminated. To this end it is recommended that the top of the elbow be vented to the test section with either a small continuous bleed or a larger capacity float-operated valve.

3. Break Planes

To permit removal or insertion of alternate test sections it is recommended that a flanged and bolted break plane be provided at the entrance to the elbow as shown in Fig. 19. For purposes of assembly it may also be desirable to have a similar break plane at the elbow exit, although this is probably not necessary.

D. Fabrication and Surface Finish

The exterior pressure walls of the elbow are expected to be a welded assembly of flat and rolled plate. The vanes can be either a welded assembly of rolled plates and a formed nose or a cast or forged assembly. The prefabricated vanes are presumed to be welded to the walls.

Design values for the water load on the vanes should be computed for a local velocity of not less than 35 fps. The model vanes, which were cast

bronze bolted to the housing walls, operated at local velocities up to 43 fps with no evidence of noise or vibration.

Because of the high velocity on the vanes and the accompanying potential for cavitation and flow separation, smooth finishes and close adherence to dimensional values are necessary. Lower velocities and simpler shapes permit relaxed requirements for the housing walls. The required surface finishes are listed in Fig. 39.

E. Observed Velocities and Cavitation

The velocity profiles for the flow entering the elbow are the same as those for the flow exiting from the main diffuser. These profiles are shown in Fig. 18 and discussed in section V.

The velocity profiles for the flow downstream of the elbow are shown in Fig. 20. These profiles appear quite acceptable, as do the energy loss values calculated from the profiles and summarized in section VIII.

With the velocity data of Fig. 18 and the previously established critical Sigma value of 2.25 for the vane, computations can be made to determine the vane's probable susceptibility to cavitation. Such cavitation should occur, if at all, with the highest test section velocity--100 fps--and the lowest operating test section pressure head, or about vapor pressure. For such computations the data of Fig. 18 relating to $V \approx 50$ fps with the 1/2 inch vortex generators are most pertinent. These data show about a 42 per cent ratio of mean to maximum elbow velocity. For the given dimensions this gives a maximum elbow velocity at the vanes of 35 fps.

If a Bernoulli equation is written between the centerline of the test section and a point just upstream of the vane using the above data and an appropriate value of diffuser head loss from the energy summary of section VIII, local pressure conditions at the elbow can be computed. If this local pressure and the local velocity of 35 fps are applied in the expression $\sigma = (P_L/\gamma - P_{VP}/\gamma)/V_L^2/2g$, a Sigma value can be computed. For these conditions σ will be several times greater than the critical 2.25 cited earlier. Hence the possibility of local cavitation on the vane does not exist. This conclusion has been confirmed by visual observations through the elbow window under high speed conditions. Cavitation is suppressed in this case primarily by the large pressure regain through the diffuser. While cavitation does not appear to be a problem in the elbow when it is

connected to the 3 ft by 3 ft high-speed test section of Fig. 3, the alternate low-speed test section routes much more flow through the elbow and has a diffuser which provides much less pressure regain. Cavitation may or may not be a problem, depending on the velocity profiles issuing from this diffuser. The current tests did not extend to the alternate test section.

VII. DOWNCOMER

The downcomer has three principal functions:

1. It accomplishes a shape transition from the 8 ft square cross section at the elbow discharge to the 8 ft $\pm$ circular cross section at the pump entrance.
2. It provides the necessary cross-sectional area change between the elbow discharge and the pump entrance.
3. It provides a diffuser connection for returning the skimmed water flow to the main recirculating flow.

A wide variety of shapes and dimensions could be employed to accomplish the flow functions listed above. The final selection depends very much on the size of the pump entrance or suction and on the form of elbow used in the pump. Since these dimensions will remain to be established later by the pump builder, this discussion will relate to the model tests, which employed an available 24 inch diameter pump. The configuration of the downcomer suggested by these tests is shown in Fig. 21 with prototype dimensions.

From the dimensions shown it is apparent that the flow generally contracts in going from the elbow exit to the pump entrance. More energy economy might have been obtained if the elbow had been made smaller. However, because of the potential for cavitation in the elbow vanes during operations with the large alternate test section, the elbow dimensions were increased to those shown. Thus the shape transition at the top of the downcomer also serves as a mild contraction. In the model, the shape transition was weld fabricated from curved, brake-formed corner plates and triangular flat gore plates. The lower portion of the downcomer was made in a simple cylindrical form.

Break planes are probably not essential in the prototype field fabrication or for future use of the downcomer itself, but it may be desirable to include a break plane at the top of the downcomer where it joins the elbow. Field assembly of the pump and possible future pump maintenance needs will probably make it desirable to include a break plane at the pump entrance.

The details of the structure which diffuses the returning skimmed flow into the main flow of the downcomer are shown in Fig. 21; the structure is associated with the return system sketched in Fig. 16. In these two figures the skimming pump discharge pipe bifurcates just above the control valve, thus slowing the flow. These two pipes discharge into the large cylindrical portion of the downcomer just below its junction with the shape transition. The two pipes are arranged so as to be both normal to and symmetrical to the large pipe at points diametrically opposite each other on this pipe. Within the large pipe the exits of the smaller pipes are shrouded by a steel liner cylinder which constrains the skimmed flow to pass up and over the shroud plate or axially downward at the bottom. This provides two exits for the flow, both through 3/4-inch-wide throttling slots in an axially downward direction. Area restraints in the exits force the flow to become somewhat uniform around the peripheral slots.

No detailed measurements have been made to evaluate the output quality of the diffuser, because Pitot velocity profiles made just above the pump intake in the model have indicated an acceptable general distribution of velocity. Dimensional tolerances and surface finishes are not considered critical; their values are listed in section XVI.

VIII. ENERGY AND PUMP REQUIREMENTS

A. General Considerations

The function of the recirculating pump in the channel loop is to supply energy to the water in such quantity and manner as to maintain the desired flow conditions in the facility test section. The primary problems in arriving at the best selection for the pump are

1. Establishing the maximum or critical performance demanded of the pump in terms of discharge and head necessary to satisfy the operational requirements of the facility.

2. From the established demands and prior art, determining the preferred type and size of pump.

3. Examining the performance characteristics or criticals of the selected pump with respect to its suitability in satisfying the facility flow needs at other than high or maximum flow rates.

Important secondary requirements to be considered are

1. That the velocity of the stream discharging from the pump be as precisely controllable and as free of fluctuation or drift as possible. Since the flowing mass in the channel loop is very large, the mass inertia or flywheel effect is also very large. Because of this, short time variations are not contemplated, but long-time drift could be generated by various sources. It is assumed that suitable controls in a variable speed drive could adequately counter such drifts.

2. That flow in the test section be substantially free of rotation. Such rotation is suppressed rather than generated by most of the tunnel circuit components aside from the pump. Certain types of pumps, most notably the axial flow type, inherently contribute rotation to their discharging flow unless fitted with corrective vaning. Specifications should require that the vaning correct most of the discharge rotation at all rates of flow. Pump discharge rotation is probably of less importance in the proposed loop of Fig. 3 than it was in previous NSRDC tunnels because of the substantial

rectification provided by the proposed new air separator and its diffuser.

3. That normal channel operations be possible with the pump operating at a relatively high energy efficiency. This is important not only for conservation of input energy and reduction of thermal build-up, but also because low efficiency introduces pressure pulsations or turbulence as a by-product of separation and vorticity.

4. That the pump be as free of cavitation as possible. This applies not only to the substantial cavitation that could yield reduced performance, but also to any minor local cavitation that might produce significant background noise in the channel system.

In considering the above requirements it is important to appreciate that the pump for the proposed facility will be a custom-built machine of a type that can be supplied by only a few specialized makers. It is unlikely that any maker has supplied a machine that closely duplicates the needs of this pump. It will, therefore, probably be necessary to require model studies by the pump maker to clearly establish his ability to meet the above requirements. Since the desired information is not available to the consumer-engineer prior to such tests, he is confined to formulating somewhat idealized specifications which the maker may or may not be able to achieve precisely.

B. Discharge-Head Relations

The maximum discharge requirements of the channel pump are fixed by the test section size and the maximum test speed initially specified by NSRDC. As discussed earlier, two test sections were considered: essentially a 3 ft by 3 ft test section with a maximum mean velocity of 100 fps and a discharge of 900 cfs and a 6 ft by 4 ft test section with a maximum mean velocity of 50 fps and a discharge of 1200 cfs.

The head against which the pump should operate would be variable and would depend on the selected discharge. This head is a function of the design flow efficiency of the total channel loop constituted of various loop components. In an attempt to evaluate the magnitude of the total energy head requirements for the purpose of preliminary pump design, prior art was examined for the energy losses which might be contributed by each of the major flow components of the channel circuit. This background involved pipe

friction theory, related component studies for wind tunnels, and previous water tunnel studies, most notably those done at St. Anthony Falls for the development of the present NSRDC 36-inch water tunnel. In addition to prior art investigations, limited special experimental tests were conducted under the current study to evaluate head loss in the new type of separator and diffuser and in various components of the model channel. The information obtained has been summarized for the proposed new facility in conformance with a method developed many years ago for wind tunnel studies. According to this method, energy head values are determined and expressed for each significant individual energy component of the channel loop and these components are then summed to yield the total energy needs. To facilitate comparisons, all losses computed by this method are arbitrarily expressed as a portion of the kinetic energy that will exist in the test section jet at a given velocity.

The test section kinetic energy per pound of water, E, is given by $E = V_o^2/2g$ where V_o is the mean test section velocity in fps.

The total energy of the test section flow, expressed in horsepower, is

$$HP = Q\gamma E/550$$

where Q is the discharge in cfs and can be expressed as $Q = V_o A_o$ where A_o is the cross-sectional area of the test section and γ is the specific weight of fresh water ($\gamma = 62.4$ lbs/cu ft).

For the maximum design flow of $V_o = 100$ fps in the 3 ft by 3 ft test section the jet energy is

$$HP = [(100 \times 3 \times 3)\ 62.4 \times 100^2/2g]/550 = 15{,}800\ HP$$

The rate of energy input required to maintain the above jet energy is the summation of the losses of the individual circuit components and can be expressed as

$$HP = V_o A_o \gamma[\Sigma K_o\ V_o^2/2g]/550$$

In using experimental data to establish K_o in this equation, it is usually convenient to first interpret the local loss of a component as $K_n V_n^2/2g$, where V_n is the local mean velocity through the effective

cross-sectional area A_n of the particular component. These local energy head loss values can be normalized to the K_o base by employing the discharge continuity equation

$$Q = Q_n V_n = A_o V_o$$

This leads to a relation between local loss expressions and the loss expression in terms of test section values of

$$K_o = K_n (A_o/A_n)^2$$

On the basis of this method of summarizing the energy demands, the K_o values for the various circuit components are tabulated in Fig. 22 for both the 3 ft by 3 ft test section and the alternate 6 ft by 4 ft test section. These values relate to the prototype dimensions of Fig. 3.

As previously noted, measurements were made of the velocity profiles and pressures at various locations in the model channel for head loss evaluations. These measurements were made at the entrance and exit planes of the first elbow, at the entrance to the pump elbow, immediately downstream of the pump diffuser, at the entrance and exit of the lower leg elbow, at the entrance of the upcomer elbow, and in the air separator. The velocity profiles were integrated to obtain kinetic energy correction factors, α, at each of these locations. The total head loss then determined was divided into two components, a form loss and a friction loss. Friction loss was calculated for the model channel component and subtracted from the total loss to obtain the form loss. This form loss was assumed to be independent of velocity (an assumption generally validated by the measurements), scaled to the prototype, and added to the calculated friction loss in the prototype based on a 250 rms surface finish. Losses in the test section were calculated using skin friction coefficients from two-dimensional flat plates with the appropriate surface area and roughness.

It should be further noted that some of the components in the small scale channel are not truly models of the prototype. This is particularly evident in the case of the main diffuser, which will have a higher area ratio in the prototype than that modeled as a result of including the possibility of the larger alternate test section. The loss coefficients shown in Fig. 22 for the main diffuser are based on the model measurements for form loss with

added friction losses for the higher area ratio diffuser. Elbow values were extrapolated from the model measurements. These values are subject to question, as a change in the diffuser will also probably result in a change in the loss in the elbow due to mutual interactions. However, the form loss in the model diffuser was higher than expected; this was assumed to be associated with the design of the floor transition, as previously mentioned. Furthermore, the drag of the vortex generators installed in the model was not subtracted due to the difficulty in estimating the drag under various flow conditions. Thus the tabulated diffuser values are felt to be conservative.

It should also be noted that the energy loss values are given for both the bare test section and a test section fitted with a high drag test body. For purposes of calculation, the test body was assumed to have a diameter one-sixth of the test section dimension and a drag coefficient of 1.00. In addition, the test body was considered to adversely influence the diffuser loss.

In the model, losses were measured in the main diffuser with the test body shown in Fig. 6 installed in the test section. This body added a loss to the flow circuit of about $0.015\ V_o^2/2g$. Measurements at test section velocities of about 30 and 50 fps indicated that the diffuser loss remained essentially the same at 30 fps, but actually decreased slightly at 50 fps rather than increasing. However, time did not permit further investigation of this effect, and thus for calculation of the prototype losses it was assumed that the form loss in the diffuser was increased by 50 per cent due to the presence of the test body.

The energy loss coefficients for the alternate 6 ft by 4 ft test section have been scaled from the model tests wherever possible and calculated in other components. The form loss in the main diffuser was assumed to be slightly lower here than in the high-speed test section.

The determination and study of the K_o values for various elements of the channel lead to an insight into the influence and importance of component energy efficiencies. From this it can be concluded that most of the losses occur in the upper leg of the channel loop. However, it should be noted that additional insight into the total channel energy demands is obtainable through determination of a parameter known as the "energy ratio." This quantity is sometimes defined as the ratio of the external power input

to the power of the test section jet. For the current estimate it will be assumed that an electrical drive delivers 95 per cent of the input energy and that the pump efficiency is 85 per cent at maximum, but possibly only 80 per cent for test conditions. To provide additional insight into energy demands, values of this energy ratio have been added to Fig. 22 and input electrical energy curves have been added to Fig. 23.

The calculated head-discharge curves based on the estimated losses in the prototype are plotted in Fig. 23 for both test sections with and without the test body. Maximum head required for the high-speed test section is about 54 ft, while the alternate test section requires about 20 ft.

C. Pump Cavitation

Since the facility is designed to provide relatively severe cavitation conditions in the test section, all tunnel elements in the low pressure region between the test section and the pump should be suspected of operating with possible local cavitation problems. The pump is particularly suspect because of the high relative blade velocities that are involved in its operation. To prevent such cavitation the proposed tunnel circuit must be examined relative to the discharge-pressure conditions that will exist at the pump entrance for projected operating conditions. This available pressure must then be checked to see that it exceeds the suction pressure requirements of the proposed pump. These comparisons are most effectively made by employing suitable cavitation σ values for the tunnel and the pump. The pump σ value required to avoid cavitation as employed herein is given by

$$\sigma = \frac{P_s - P_{vp}}{\gamma} \Big/ H$$

where P_s = absolute static pressure at the top of the pump impeller in lbs per sq ft

P_{vp} = vapor pressure in lbs per sq ft

γ = specific weight of fluid in lbs per cu ft

H = head added by pump in ft

Application of the above index shows that the least tolerable value will occur when incipient cavitation exists at the crown of the channel diffuser transition (designated by the subscript d). Using this point as

a minimal pressure source, the pressure at the top of the pump impeller at the pump suction (designated by subscript s) can be computed by relating the pressures at these points through a Bernoulli energy equation thus:

$$\alpha_d \frac{\overline{V}_d^{\,2}}{2g} + \frac{P_d}{\gamma} + Z_d - h_\ell = \alpha_s \frac{\overline{V}_s^{\,2}}{2g} + \frac{P_s}{\gamma} + Z_s$$

where α = kinetic energy correction factor

P = absolute pressure in lbs per sq ft

$\overline{V}$ = mean velocity of flow in fps

Z = height above datum in ft

h_ℓ = head loss between d and s

For calculation of σ it was assumed that $\alpha_d = 0.9$, $\alpha_s = 1.1$, $A_s = 42.3$ sq ft, and $P_d = P_{vp}$. The area of the pump suction was determined using an 8 ft diameter pump with a 40 per cent hub-diameter ratio. The other terms were taken as $Z_d - Z_s = 33.71$ ft, $A_d = 9$ sq ft, and $h_\ell = 0.215\ V_d^2/2g$ for the high-speed test section and $Z_d - Z_s = 34.21$ ft, $A_d = 24$ sq ft, and $h_\ell = 0.240\ V_d^2/2g$ for the alternate test section. The pump head was assumed to be midway between the bare channel and test body curves of Fig. 23.

The resulting expressions for σ are

$$\sigma = 2.02 + \frac{107.5}{V_d^2/2g}$$

for the 3 ft by 3 ft test section and

$$\sigma = 0.644 + \frac{71.8}{V_d^2/2g}$$

for the 6 ft by 4 ft test section. These curves are plotted in Fig. 24 as a function of pump discharge. The question is now whether the prior act of pump design can be expected to define a pump with cavitation susceptibilities that are better than these facility potentials. Exact values of a pump's cavitation tolerance are best defined through model tests of the particular machine to be used.

IX. LOWER LEG

The lower leg of the tunnel is a simple cylindrical pipe connecting the discharge end of the pump diffuser with the entrance to the third elbow. Its size is not critical and is a loose compromise between initial installation costs and ultimate energy operating costs. The selected diameter of 11 ft as shown in Fig. 3 operates with a mean velocity of 9.5 fps for maximum flow in the small test section and about 12.5 fps for maximum flow in the large alternate test section.

The lower leg is the lowest part of the channel loop, and channel drainage should be provided at a convenient point along its length.

X. UPCOMER AND ELBOWS

The upcomer pipe and elbows three and four serve as a connecting flow conduit and turning structure between the lower and upper legs. The conduit size, like that of the lower leg, is not critical, and an 11 ft diameter, the same as that of the lower leg, has been selected.

The two elbows involved were designed according to the same basic concepts as the first elbow, which was described in section VI. However, the design is somewhat different in that elbows three and four operate at a much lower velocity and are housed in circular rather than square sections. This leads to quite different vane structural loadings and end attachment geometries. Although the same type of thickened vane used in elbow one could have been used in elbows three and four, that type is believed to be more costly than a bent plate type of vane. The bent plate type is equally satisfactory from the standpoint of flow considerations provided support struts can be kept few in number. The thin bent plates are structurally weaker than the thickened vane and usually require intermediate supports. These supports, like end supports, generate secondary flows and energy losses and should be minimized. However, using one or two intermediate supports would not seem to create a serious problem. Figure 25 shows the bent plate assembly used in the 24 inch diameter third elbow of the model channel (also used in elbow four). In this removable vane assembly the vanes are supported solely by the two struts without end attachment to the tunnel walls. The assembly provided good flow turning and head loss values.

A layout for the type of vane shown in Fig. 25 is given in Fig. 26. Detailed dimensions will result from adapting this layout to a given elbow with an arbitrary number of vanes; this number can range from about 8 to 12. Structural studies of the hydrodynamic loading on the vane should assume a water velocity of no less than 150 per cent of the maximum mean flow velocity.

XI. SCREEN DIFFUSER

The function of the screen diffuser is to reduce the relatively high velocity of the recirculating conduit flow to the very low values required for air removal in the separator. As was stated in section X, the velocities discharging from elbow four will have average values as high as 9.5 fps for the small test section and up to 12.5 fps for the alternate large test section. The corresponding value in the separator has been fixed as 1.0 fps for operation with the small test section. In consequence the separator diffuser is required to have an area expansion ratio of 9.5.

The selected diffuser area ratio is a very large value in terms of the prior art of simple conical diffusers and would moreover require a very long and costly structure if the usual low included angles of 5 to 10 degrees were used to achieve good energy recovery. As an alternative, consideration might be given to providing a very rapid expansion with a compact, low-cost structure that entailed acceptable energy losses. Because the entering flow in this case has a moderate velocity of only 9.5 fps, the resulting available kinetic energy head is low (1.4 ft) and the head loss at most will not be serious if an adequate and simple short diffuser results.

In this case the short diffuser adopted follows the work of Schubauer and Spangenberg* with supporting data values for perforated plates rather than screens drawn from the work of Baines and Peterson**. Based on these papers a short conical diffuser with an internal angle of 90° was selected for the outer housing. Within this housing, four planar screens are to be spaced as shown in Fig. 27. Each screen is to consist of a metal plate with perforated circular holes having a uniform pattern in which approximately 42 per cent of the total area is solid.

In the model diffuser these needs were satisfied by a commercial screen with 1/4 inch round holes on staggered 5/16 inch centers. This screen was made of 0.037 inch thick stainless steel. To facilitate fabrication, installation, and possible removal, the perforated sheets were

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*Schubauer, G. B. and Spangenberg, W. G., Effect of Screens in Wide Angle Diffusers, NACA Technical Note No. 1610, 1949.

**Baines, W. D. and Peterson, E. G., "An Investigation of Flow through Screens," Trans. ASME, July 1951.

assembled in elements as shown in Fig. 28 (a) and (b). In these welded elements, support plates and bars stiffened the thin sheets against hydrodynamic loadings. The individual elements were bolted to the interior of the conical housing and to each other as shown in the partial assembly of Fig. 29.

For the large prototype it is suggested that a somewhat similar unitized construction be used. For this construction a thicker plate with large holes would be advantageous, and holes up to 3/4 inch in diameter and plate thickness no greater than 1/8 of the hole diameter would be acceptable if the solidity ratio were in the range of 40 to 45 per cent. In no case should the solidity ratio exceed 50 per cent. Perforated plates with larger holes are commercially available.

The prototype assembly should be such that gaps between assembly elements and between elements and the conical housing can be covered or packed in the field assembly to prevent excessive local blow-by.

In the model studies, Pitot cylinder velocity traverses were taken just upstream of the fourth elbow and current meter velocity traverses were taken just downstream of the fourth screen to establish the action and flow quality of the diffuser. The traverses run just downstream of the screen were on a diameter at a slope of about 45° running from the upper left to the lower right in Fig. 29. Figure 30 shows typical velocity profiles for the upstream station, and Fig. 31 shows typical profiles initially obtained immediately downstream of the fourth screen. The irregularities of the profiles are due to local wakes of some of the structural members supporting the resistance screens. Most of these wakes are expected to decay before the flow enters the gas separator. The profiles of Fig. 31 were very undesirable in that a substantial part of the flow had a much greater than average velocity. This was not a desirable condition to impose on the downstream gas separator in which local velocities exceeding one fps would produce carry-through of gas bubbles in excess of the desired size. The profiles indicated a deficiency of resistance capability in the central portion of the diffuser.

In order to flatten the model velocity profiles downstream of the diffuser, resistance was added to the four center elements shown in Fig. 28 (b). This was accomplished by simply overlaying an identical screen on the upstream side of the initial screen and displacing the two

patterns of holes to decrease the effective hole area. This area change was slight, as the maximum recommended solidity ratio is 50 per cent.

Velocity profiles were obtained after this modification to enable assessment of the improvement in profile flatness. A definite improvement is indicated, as shown in Fig. 32. The irregularities due to the wakes of the structural members are of course still present. The performance of the screened diffuser in terms of both the flatness of the profile and the acceptable overall performance of the gas separator is considered satisfactory. The nature of the flow is such that scale effects should be negligible, and prototype performance should be equally acceptable.

It is quite probable that the prototype installation will require in-place resistance adjustments similar to those which were necessary in the model. For this purpose it is suggested that an additional layer of screening be provided together with attachment and adjustment features. A resistance increase across the central 30 to 40 per cent of the diameter is considered adequate. In addition to the screen provisions it will be necessary to provide an access hatch for entry to the space between the screens and the air separator. Support and access for velocity profile instrumentation will also be needed.

Energy losses for this diffuser are difficult to evaluate separately, but the satisfactory overall energy requirements indicate that the diffuser is acceptable.

The surface finish of the diffuser interior is in no sense critical because of the high turbulence being created by the screens. The screen elements of the diffuser should be adequately stiffened and reinforced. Vibratory conditions have been reported for some screens, although no evidence of vibration was observed in the model tests.

XII. AIR SEPARATOR AND FLOW STRAIGHTENER

A. Air Separator

In earlier parts of this report the need for control of the free gas content of the test section flow was described and data evaluating certain of the test section air characteristics of the model of the proposed channel were included. In this portion of the report the components of the tunnel which provide major control of the free gas will be discussed with respect to function, rationale, configuration, and construction.

For the proposed new facility the specified range of test section test conditions requires that the free air content range from a value of zero to about 10 volume parts per million at test section entrance to 3000 or more vppm at exit. Quite obviously, something in the channel loop must separate out and reject this excess of air. It is the objective of the air separator component to do this.

A variety of mechanisms can be employed to separate free air bubbles from water, but as mentioned in the earlier feasibility report for this facility*, a gravitational separator was used for the study. The particular form of gravitational separator that was used was a tube type developed at St. Anthony Falls and first reported on in 1958.

A gravitational separator depends on the fact that the unit weight of free air is only about one-tenth of one per cent of that of water. This provides an inherent gravitational instability and tends toward phase separation whenever free air exists in water. The separation of air bubbles from water is closely tied to the physical size of the bubbles involved. The size is in turn quite dependent on the previous history of the bubble. It should be noted that a bubble exists as a finite entity in water because of an inherent interfacial tension force. This force is sufficiently strong that several small bubbles coming in contact very readily coalesce into one large bubble, and continuing growth by this process is difficult to arrest in quiet water. The inherent surface tension of water is too weak to resist mechanical shear of any consequence. Hence gravitational separation of air will be promoted by the provision of regions of low shear or low velocity. In such regions the rate of separation of the air is dependent on the rate at

*Ripken, J.F.; Wetzel, J.M.; and Schiebe, F.R., A Hydrodynamic Feasibility Study for a Large, High-Speed, Variable Pressure, Free Surface Water Test Facility, Memorandum No. M-132, St. Anthony Falls Hydraulic Laboratory, Univ. of Minnesota, April 1972.

which bubbles coalesce and rise. A study of the nuclei air bubble needs of the test section indicates that bubbles having rise rates between about one and 30 cm/sec are in the range that a gas separator should seek to remove. Removal can be accomplished by providing a quiet flow channel or conduit in which the dimensions and detention time will permit the smaller bubbles to rise to the top for collection or removal before the water exits from the conduit.

For a large quiet flow in a single conduit of considerable depth, the required detention time for removal of all bubbles of a specified small size will require a very large length. A fairly simple approach to reducing the size of the separator is through subdivision of the depth into a large number of units, each having a small vertical dimension. In the St. Anthony Falls separator the depth reduction is achieved by breaking the total cross section into a large number of tubular passages of small depth. The selected tube configuration represents a compromise between shapes and sizes which might be preferred for flow control and those which could be practically fabricated and assembled for mass installation in a large flow facility. The shape, size, and orientation were selected based on early comparative trials.

A flow tube with a crown shaped to a sharp inverted V, in which a thickened boundary layer developed, was chosen. Bubbles which managed to gravitate upward into this boundary layer were exposed to relatively low velocities and a weakened transporting system. With the tube axis tilted downward in the direction of flow, the bubbles coalescing in the crown of the tube were subject to a gravitational-force component acting upstream along the top of the tube.

With appropriate adjustment of the tube slope and the mean flow velocity, it has been established that it is practical to promote the collection and upstream movement of nearly all but the smallest sizes of bubbles passing through the tube. To promote general collection of the bubbles, the individual tubes are provided with holes near their upstream ends. These holes intercept the bubbles moving upward along the tube crown and bleed them from one tube to the next above. With a stacked bundle of tubes the bubbles eventually gravitate up to a ceiling plate from whence they are bled off laterally and vertically to the crown of the main separator housing and thence back to the test section.

Pilot studies of various tube configurations and arrangements led to the use of commercially available corrugated fiberglass-reinforced plastic

sheets stacked to produce the desired tube arrangement as shown in Fig. 33. The corrugated material was in this case approximately 1/16 inch thick with a corrugation pitch of 2.67 inches and a corrugation depth of 7/8 inch. To permit gas migration, the corrugated sheets were fitted with seven saw slotted holes of 1/4 inch width, 1/2 inch length, and 2 inch spacings beginning 1/2 inch from the upstream end of each corrugation. The sheets were riveted together with aluminum rivets near both ends and at various intermediate points to form bundles as shown in Fig. 34. These 27-inch-long bundles were stacked in a grid of metal separator plates (see Fig. 29) which positioned the bundled tubes at an angle of 20 degrees with the horizontal. The sides of all bundles which abutted the vertical metal separator plates were terminated with a flat sheet of fiberglass-reinforced plastic riveted to the side of the bundle. This permitted air capture in the last half-tube units. The terminal flat sheet can be seen in Fig. 35.

The available fiberglass-reinforced plastic sheets were not uniform in dimensional pitch and flatness, with the result that the contact lines between neighboring corrugations did not all meet perfectly. To prevent air leakage, the cracks were closed by additional riveting and by sealing with a caulking gun type silicone sealer.

Later studies in the model indicated that random carry-through of larger air bubbles could be materially reduced by locally adding additional flow resistance to the inverted V at the crown of each tube. This was accomplished by placing a small stretched spring in the V as shown in Fig. 33 and clipping its end hooks to the fiberglass-reinforced plastic. The spring was made of 0.015 inch stainless spring steel and wound to a diameter of 1/4 inch. The tightly wound spring coils had a spacing of 1/8 inch when stretched in place. This spacing provided ready vertical access for the collection and coalescence of the air bubbles at the tube crown, but impeded their downstream longitudinal transport.

Most of the geometrical features of the model tunnel are scaled up for prototype use by a factor of 4.8. However, it must be stressed that this does not apply to the dimensions of the air separator tubes. The dimensions of these tubes are essentially absolute and remain fixed regardless of the total size of the facility in which they are used.

In the model, the tube bundles were made up in approximate cubes about 27 inches on a side and were shaped to conform to the confines of the cylindrical

housing of the separator. The 27 inch length of the tube bundle must remain fixed, but the width and height dimensions are not critical. The dimensions used in the model were convenient for external shop fabrication and for field installation. In the prototype the separator housing is to be 34 ft in diameter, and a substantial number of tube bundles will be needed to fill the cross section. It is suggested that the height of a tier in this assembly be no more than about 3 ft. Tiers higher than this may be subject to gas overloading in the upper tubes of the tier under heavy gas loads in the channel loop.

The horizontal members of the grid of the metal plates (partially shown in Fig. 29) which serve to shelve the tube bundles also serve as collector ceilings for an individual tier of tube bundles. Air gravitating upward out of the tube bundle rises to the sloped ceiling plate and then moves upstream. In the model the ceiling plate was terminated at the upstream edge with a bent lip as shown in the partial assembly of Fig. 35. The bent lip serves to collect the air escaping from under the roof. It does this in a horizontal 1-inch-by-5-inch lateral which conveys the air offside to a peripheral sheet metal duct running around the inside of the main housing (light area at top left in Fig. 35). A partial assembly of this peripheral duct is shown in the model in Fig. 36. At the top of the separator housing, the peripheral duct spills its collected air into a dome on the housing roof from whence it is bled back to the test section. At the top of the separator housing, where an air-water interface normally exists, the wall of the collector duct is perforated to allow free flow of the air to the roof dome. The appended roof dome needs to provide only a relatively few square feet of free surface and a modest volume. As will be discussed in section XV, a larger free surface would sometimes be used for control purposes, and this would be maintained in the upper portion of the 34 ft housing structure rather than in the roof dome proper.

The bent-lip collection lateral also proved to have other benefits. First, it tended to impede flow and locally reduce velocities just below the ceiling and thus to promote air transport upward along the ceiling. Second, it permitted the leading edge of the tube bundle in the tier above to be advanced upstream by 5 inches. The stepped front on the tube bundles permits a shortened length for the assembled 34 ft high stack as shown in the total assembly of Fig. 37.

The grid of metal plates constituting the support system for the tiered bundles of tubes should provide a minimum of flow obstruction and an assembly system permitting re-entry to the screened diffuser area.

External viewing ports, interior lighting, and an access hatch should be provided for observing and servicing the region between the air separator and the flow straightener. Model experience showed that a close fit between the tube bundles and the metal support grid was difficult to achieve, and local air blow-by was observed in regions of excessive velocity along the sides and top of the tube bundle in some cases. These areas were subsequently reduced in flow velocity by adding resistance strips as needed at the downstream end of the bundle as shown in Fig. 38. This figure also shows the bolt-on bent plates or clips which restrained tube bundles from sliding downstream on the support grid. The tube bundles were not attached to the grid.

B. Flow Straightener

Flow being discharged from the air separator tubes should have a mean angle of 20 degrees with the horizontal, while flow entering the contraction should be horizontal in direction. It is the principal function of the flow straightener to provide this turning action. It is a secondary requirement of the flow straightener that the scale and intensity of turbulence in the discharge flow be as low as practical.

In the model experiments the flow straightener was constructed of bundled units of corrugated fiberglass-reinforced plastic sheets fabricated in much the same way as the gas separator tube bundles previously described except that joint sealing was not necessary. The width and depth of these bundles were essentially the same as those of the separator bundles, but the length was only 6 inches. In this case the corrugations of the sheet were angular and were a commercially available "Alcoa Rib" of 2.67 inch pitch and 9/16 inch depth. The sheet thickness was 0.05 inch. When these sheets were riveted together in bundles, the resulting honeycomb openings were hexagonal in shape. Unlike the air separator tubes, which must be kept at essentially the same size in model and prototype, the honeycomb elements can be arbitrarily made in larger sizes provided that the length-to-width ratio of the individual tube equals or exceeds 6.

The straightener tube bundles were supported by a metal grid of plates similar to those supporting the air separator bundles, but shorter. The assembly was such that the bundles and grids could be removed for access to upstream components. Bundles were restrained in the grid by downstream clips similar to those which restrained the separator bundles as shown in Fig. 38. Because of the lesser length of the flow straightener shelves, the clips were bolted to brackets projecting downstream of the grid members. No detailed studies were made of the straightener flow action, but satisfactory model performance of the contraction was deemed adequate proof of the straightener design concepts.

C. Surface Finish

The surface finish of the outer housing of the air separator and flow straightener is not critical, because of the low flow velocities involved, nor is the "as is" finish of the metal plates supporting the fiberglass units or that of the fiberglass material.

XIII. ALTERNATE OR LARGE TEST SECTION

A. General Considerations

The high speed test section is intended to implement the testing of surface effects for the components of high speed ships with other than conventional displacement type hulls. The purpose of the large alternate test section is to provide a moderately high speed variable pressure test facility of dimensions sufficient to accommodate larger assemblies of components of surface effect ships. A test section depth of 4 ft, width of 6 ft, and top speed of 50 fps are specified.

At the time of this writing, design planning is under way to implement the construction of this alternate test section along with the construction of the high-speed channel. In the event of funding problems the alternate section may be built in a later phase of construction. The general elements of this test section are being delineated at this time, however, so that it can be integrated into the planning and properly provided for.

The proposed dimensions of the alternate large test section are shown in Fig. 40. The total length was dictated by the length which evolved in the design of the high-speed test section.

B. Contraction Nozzle

The contraction nozzle shown in Fig. 40 serves the same function as the high-speed nozzle discussed in section III. It differs principally in that a lesser contraction ratio will be required because of the larger discharge area. Because of the reduced area ratio, the contraction nozzle length was arbitrarily reduced to 8 ft, 6 inches, with the saved length contributed to the diffuser, which it was thought might benefit more from it.

The curve of the roof was based on the same concept as was used in the high-speed nozzle design and again was based on an equation of the form $Y = AX^3$ with the origin joining a horizontal tangent at the upstream end and a tangent at 30 degrees with the horizontal at the downstream end. Similarly, the curve of the bottom joins a tangent line of $39^{\circ}\ 41'$ at the entrance with a horizontal tangent at the exit. The connecting curve is again a portion of a simple ellipse. The sidewall curves again join a tangent line which is at an angle of $23^{\circ}\ 37'$ with the test section axis to a tangent which is parallel to the test section axis. The connecting curve is also a portion of a simple ellipse.

Fillets in all four corners of the nozzle are again advocated. They are to be large at the nozzle entrance and are to match the dimensions arising from the contraction transition. They will diminish in size with progress downstream. The lower fillets will diminish to the size of those which continue through the test section, while the upper fillets will diminish to zero radius at the downstream end of the nozzle. The dimensions of this configuration are given by section C-C and the table of Fig. 40.

Since the boundary curvatures of the alternate nozzle are no more severe than those of the high-speed nozzle, and the latter has performed satisfactorily in model tests, there is no reason to believe that problems will be encountered with the proposed design of the alternate. The comments in section III relating to the lip block, general construction, surface finish, air drainage, break plane, and piezometric tap apply also to the nozzle of the alternate test section.

C. Test Section

The discussions in section II dealing with the high-speed test section apply also in general to the larger alternate test section. However, the following differences should be considered:

1. Test section topside access for observers and photography may be more important in the large test section than in the high-speed unit. Accordingly, the arbitrary dome height of 7 ft could be increased. The above-water width shown as 6 ft might also be expanded advantageously. The lower water speeds may make such expansions more practical in this test section.

2. Because of the substantial increase in test section length, those quality factors in test section performance which deteriorate with length will deteriorate further with this test section. This applies particularly to the increasing loss of usable water surface width due to boundary layer growth and surface edge effects. The data measured on the model high-speed test section can be extrapolated downstream for the new prototype condition as a rough guideline, but it must be recognized that high quality surface flow conditions can be expected only at the upstream end.

3. The large model size to be tested will require larger access and handling facilities.

4. The larger volume of the gas dome over the test section will require increased vacuum and compressed air capabilities for achieving test pressure conditions in a specified time span. This volume will also affect some of the rate values of controls used in the skimmer return circuit.

5. Because of the Froude depth relation, the critical velocity for the 4 ft deep test section will be slightly greater than for the 3 ft deep section ($\approx$ 12 fps). The extent to which surface wave criticals will interfere with testing at low velocities is presently indeterminate.

6. At the maximum speed of 50 fps the large test section will discharge about 1200 cfs, compared to a maximum speed of 100 fps, or a discharge of about 900 cfs, in the small test section. These values mean that the maximum velocities in the recirculating loop will be 33 per cent higher for the alternate test section. This will have significant effects in the first elbow, pump, and gas separator. The first two items will be discussed later. The 33 per cent overload in the gas separator will produce some slight evidence of free air in the flow entering the test section, but model experiments do not show critical values occurring in the proposed range of operations.

D. Skimmer-Transition

The skimmer for the large test section will be 50 per cent longer and should discharge about 33 per cent more flow for the same percentage of skimmed depth. The model tests of the skimmer described in section IV have not clearly defined its capacity, but it appeared to handle the specified skim of 5 per cent of the depth without difficulty. A conservative approach to the larger channel skimmer would indicate that an increase of about 33 per cent in the flow areas or about 15 per cent in the diameters of the flow passages should suffice. This would apply to the diameter of the skimmer housing, the separator chamber, and the discharge to the pump as shown in Fig. 15. A similar increase in size is recommended for the pipe, reservoir, pump, and valve of Fig. 16. If possible it would be best to leave the sizing

of all these elements until the high-speed prototype has been operated and examined for possible evidences of over- or under-design.

E. Main Diffuser

The main diffuser of the large test section will operate with a much smaller area ratio and a much smaller length than the diffuser for the high-speed channel. Other things being equal, it should be a more effective diffuser with fewer separation or stability problems and no probable need for vortex generators. However, since it will be downstream of a longer test section, the inflow may be more peaked, and this may be enough to contribute to separation problems necessitating vortex generators for relief. It is suggested that in a first pass no vortex generators be installed, but consideration be given to providing for their future use.

It should be noted that the diffuser for the high-speed test section will be nearly symmetrical in cross section, whereas the alternate will not be. This is not thought to contribute any special problems.

F. First Elbow

As was discussed in section VI-E, there is some possibility that cavitation will occur in local high velocity regions of the flow through the elbow vanes. The size of the elbow was increased substantially to allay this probability, but without specific data on the shape of the velocity profile entering the elbow it is not possible to predict the occurrence of cavitation. If cavitation did occur, it would occur only in a limited area of the vaning at the highest speed conditions, which would be of rather limited duration. It is not anticipated that the cavitation would be critical to performance or seriously erosive. Moreover, because of the substantial amount of free air ingested below the skimmer, the tunnel flow will normally be fairly well aerated. Under these conditions, erosive damage or noise would probably be of little concern.

G. Pump

Pumping considerations relative to the increased discharge with the large test section are discussed in section VIII.

XIV. AUXILIARIES

A. Vacuum and Compressed Air Plant

For the desired supercharge control of test section air pressure conditions, which are to range from water vapor pressure to four atmospheres absolute, both vacuum and compressed air services must be available. Several aspects of the control of supercharge pressure are discussed in various parts of this report, but nothing has been said about the capacity of these services. An approximate fix on this capacity is established by the delay time that is considered tolerable in bringing the system to a desired predetermined test pressure value from an initial atmospheric pressure datum. This time is arbitrarily designated as 5 minutes. Since the air dome for the large alternate test section is greater in volume than that of the high-speed test section, service capacity should be based on the large test section. Consideration should also be given to the volume of the dome maintained at the top of the separator. These auxiliary services must not contribute oil or other contaminating materials to the water.

In addition to pressure limit controls on the compressed air service, it is considered desirable to provide a separate pressure relief valve for protection of the pressure housing. This should be located in the air separator dome.

B. Water Supply and Treatment

Initial filling of the channel facility and its storage auxiliaries should be with a water which is filtered to remove solids to provide a high level of clarity. Unless the water has previously been treated, provision should be made for additions of chlorine, algicides, fungicides, or other materials to stabilize water quality. These additives must not alter the normal character of the water for hydrodynamic test purposes, particularly the surface tension and basic frictional properties. The supply system should be capable of filling the entire tunnel or equivalent storage volume in not more than 24 hours. It should be possible to drain the total channel facility in not more than 12 hours.

C. Water Storage, Filling, and Draining

Expeditious operating schedules require emptying of the test section to its floor level in not more than 10 minutes and refilling to normal operating levels in the same length of time. In order to conserve treated water and minimize pumping energy, this emptying and filling will require adequate local storage capacity and adequate piping and pumping auxiliaries. The capacity of these should match the needs of the larger test section.

D. Fill Level

The level at which water fill is maintained in normal operations is quite critical to the stability of channel flow as described in section XV. The part of the recirculating loop in which level control appears most useful is the interface, which should normally exist near the top of the air separator. The channel operator should be provided with readout of this level value at all times and should have at his command such controls as will manually or automatically maintain this level to within plus or minus one inch for any selected level from the top of the contraction transition to the top of the air separator housing. These controls or others should serve as pumping limit controls for the initial filling of the channel.

E. Nozzle Pressure Drop

Pressure taps and readout facilities should be provided for sensing the overall pressure difference existing along the contraction. During operations this differential is the most sensitive available indicator of test section velocity. Readout facilities for this value should be available to the channel operator together with manual and automatic controls to vary or stabilize it within the desired operating range of zero to 100 fps. The available controls must permit preselecting and stabilizing of the pressure differential values to the same percentage values as those previously described in section II-G-2 for pump shaft speed. This electable control is to be separate from the pump shaft control and available for times when it may not be possible to depend on shaft speed alone to stabilize test conditions (see section II-G-6).

F. Pump Controls

Readout of the pump blade angle and the pump shaft speed by the channel operator should be provided for together with manual or automatic controls to yield the operational values described in section II-G-2.

G. Reservoir Level Control

The reservoir in the suction line of the skimmer pump was found to be essential to stable control of test section skimming action. Its function depends on essentially stabilizing the free surface level in the reservoir by varying the rate of pumped outflow to match the rate of skimmed inflow. The channel operator should be provided with readout of the reservoir level and both manual and automatic means of stabilizing the value through control of the skimmer pump and its valve.

H. Gas Return Piping

Gas which collects in various parts of the channel system must be removed in a controlled manner and returned to the test section dome. Three separate collectors are of concern in this respect:

1. The air separator will collect most of the air which will be exhausted or vented via test models plus air which is entrained in the surface flow and passes below the skimmer. The volume of this air is not known, but is estimated to be as much as 400 cfm at test section pressure. The return piping should provide for this volume with a head loss of not more than 2 ft of water head for the case of a wide-open control valve.

2. The reservoir located between the skimmer and the skimmer pump receives a skimmed flow which is high in entrained air. The flow expansion provided by the reservoir permits the bulk of the entrained air to gravitate out of the water before it is sucked into the pump suction pipe. This air collects at the top of the reservoir and is vented back to the downstream end of the test section. A 3 inch pipe without control valve is suggested.

3. The ceiling height of the first elbow is higher than that of the test section. Hence channel filling operations tend to trap a gas pocket at the top of the elbow. This can be vented back to the test section by a line of about 2 inch size. It is desirable to have a manually set valve in this line.

I. Temperature Limits

Because of the sizable length and weight of the filled channel assembly, physical expansion of the structure due to temperature requires provision of movable or elastic support elements and possible limits for the temperatures to be experienced. Some guide to the temperatures which might be encountered can be gleaned from the discussion of section II-J and from Fig. 10.

XV. OPERATIONAL PROCEDURES AND PROBLEMS

The presence of a free surface and the large air handling capacity of the channel present a number of operating problems. These problems and the experience acquired from operating the model channel will be discussed in the sections which follow.

A. Water Level

Prior to operation of the channel, it must be filled to the proper level. The filling should be done with all vent valves open to prevent air pockets from forming at high points in the channel circuit. The water level should be set so that when the test section dome is empty and the skimmer reservoir is at its proper operating level, the air separator dome will be filled to the desired level. This level can be calculated from the final dimensions of the prototype channel or determined by trial. The volume of water in the channel is critical because if the initial water level is too high, the test section water surface cannot be properly leveled, and if the water level is too low the air separator cannot be filled to a level sufficient to maintain good flow conditions in the main diffuser.

It will not usually be necessary to add or remove water from the channel during a run. The effect of a varying amount of entrained air in the channel circuit can be absorbed by varying the water level in the skimmer reservoir or in the air separator dome. Only in a case in which an extremely large amount of air was entrained would it be necessary to remove water from the channel.

The line venting the first elbow should be closed when the filling operation is completed. The contraction air vent line should also be closed until it is determined that it is necessary for removing excess air.

B. Starting Procedure

During the model studies the most satisfactory starting procedure was to begin pumping with the test section water level approximately normalized. Following an initial water fill to the proper level, the air separator dome vent line is closed and the test section is vented to the atmosphere. Water is drawn into the air separator dome from the test section by applying a vacuum to the air separator dome. When the water level in the test section

reaches the level of the contraction lip, the vacuum is turned off and the channel is ready for starting.

The initial starting procedure consists of three steps in rapid succession:

1. The main pump is turned on and set to give a sufficient velocity to establish a flowing free surface. A speed of 15 to 17 fps worked well in the model.

2. As soon as the flowing free surface is established, the air separator dome vent valve should be opened sufficiently to prevent excessive air build-up in the air separator.

3. When the flowing free surface is established, the skimmer pump should be turned on and the pump and valve set for a moderate skim rate. The rate of pumping from the skimmer should be increased until the skimmer is freely draining into the reservoir of Fig. 16 and a free surface is established in the reservoir. The skim rate should then be decreased to the level required to maintain the free surface in the reservoir at the desired operating position.

When the channel has been allowed to stabilize at the starting settings, it is ready to be brought to the desired run conditions.

C. Channel Operation

1. Vent Valve Settings

All lines venting air back to the test section dome should be carefully adjusted to insure that they carry a continuous flow of either air or an air-water mixture. The channel flow may become unstable due to the surging in vent lines allowed to carry air and water intermittently.

2. Air Separator Water Level

If the channel is to be operated with an air volume in the air separator, a very good metering valve will be required which can precisely control air flow varying from zero to the maximum expected air entrainment rate. The maximum capacity of the valve should be several times greater than the 200 cfm specified in section I to assure that large unexpected air surges can be accommodated. The valve should be controlled to hold the water level

at a constant position, because any change in the water level causes a change in the pressure drop across the nozzle, and thus if the water level drifts, the test section velocity will also drift.

Most of the model runs have been made with the air separator full of water and with the vent line carrying a continuous air-water mixture. This was found to give the most satisfactory control over the most widely varying run conditions. It is recommended that the prototype be operated with the air separator full of water unless the air volume is required as a cushion when very large, rapid changes in the rate of air entrainment are expected or when very low velocity runs are to be made (see Item 3).

3. Minimum Test Section Velocity

The minimum test section velocity with the most favorable contraction conditions will be dictated by the head required to submerge the roof of the contraction nozzle. From section III-A the minimum head is 2.9 ft; the corresponding minimum velocity is approximately 13.7 fps.

Lower velocities might be obtained by operating with the contraction only partially submerged or by applying a vacuum to the air separator dome to submerge the contraction. The model was not run under these conditions, however, and thus their effect on flow conditions and stability is unknown.

4. Controlling Velocity

Velocity is controlled by changing the main pump speed and blade angle. The skimmer return flow rate will have to be changed to compensate for the change in the flow entering the skimmer as the velocity is changed. It is recommended that the velocity be changed slowly to allow the skimmer system to respond to the varying skim rate. The changing pressure in the air separator will also require an adjustment of the dome vent valve when the velocity is changed. Rapid increases in the velocity may also cause excessive power surges to the main pump motor.

5. Controlling Pressure

The test section pressure can be varied throughout the total range without affecting the channel flow conditions. When the air content of the water is a concern it may be advisable to adjust the pressure beyond the desired setting for a short time to decrease the air content stabilization time as discussed in section II-K-1.

6. Controlling Skim Rate

It is desirable to keep the skimmer height at its neutral position to provide the best geometric entry conditions into the main diffuser. For this skimmer setting the skimmer pumping rate can be maintained at a low level; high skim rates are not required for satisfactory test section flow. Skim rates of 1 to 2 per cent of total channel flow were normally run with the model channel.

The skim return pump or valve will have to be adjusted to maintain the proper water level in the reservoir in the skimmer circuit. If the water level in the reservoir drops too low, the skim return pump will begin to ingest large amounts of air and the pump performance will become erratic. During runs with the air separator full of water the reservoir can be used as a cushion to accommodate varying rates of air ingestion.

7. Flow Breakdown

Caution should be exercised when experimenting with new or unusual test conditions to minimize the chance of a flow breakdown and the resulting violent flooding of the test section. These flow breakdowns occurred several times during the model channel shakedown runs and presented no threatening structural problems. The flow breakdown usually occurs only after a relatively slow deterioration of test section flow conditions and, with alert action by the channel operator, can be prevented. When flow breakdown occurs, the free surface can usually be restored by reducing the velocity and allowing the test section to drain to normal level. If this is not effective, the channel may have to be stopped and restarted.

The chance of a flow breakdown is always present, and the channel and test models should be designed with that fact in mind. Any components mounted within the test section should be designed to withstand submergence.

At no time should the channel be operated with personnel in the test section.

D. Shut-Down

The test section velocity should be decreased and the pressure reduced to atmospheric before the main pump is turned off. This will allow the flow to break down and the test section to flood gradually, thus preventing any unnecessary violent loading on test section components and also preventing potentially damaging transient loading on the main pump blades.

XVI. SUMMARY OF SURFACE FINISHES

In the high velocity regions of the channel, misalignments, offsets, or other forms of surface roughness may contribute detrimentally to the quality of flow or to secondary cavitation problems. It is assumed that most components of the channel flow circuit will be fabricated as weldments from steel plate with stainless cladding. These surfaces would be used essentially as rolled (this is the basis for a finish of 250 RMS) with care being taken to minimize joint misalignment from the welding assembly. General tolerances should be in accord with standard unfired pressure vessel codes.

The more critical high-speed regions are nearly all contained within the removable components of the test sections. These components and their required finishes and tolerances are given in the summary table of Fig. 39. The units of roughness in the table are root mean square values in micro-inches. An additional critical element not included within the test section proper is the vaning of the first elbow. This has been added to the table and relates to the vane dimensions as shown in Fig. 19.

XVII. STRUCTURAL LOADS DUE TO DYNAMIC PRESSURES

Section II-H discussed the specified supercharge pressures required in the test section in terms of the functional needs for these pressures in future operations. However, it must be recognized that the pressure loads imposed on the containment structure of the channel may be considerably greater than the test section operating pressure due to the contributions of static and dynamic water pressures. For structural design purposes the sum of these three pressures is most significant, and this total pressure varies in different parts of the channel loop. A graphical summary of the various total pressures in the channel loop is given in Fig. 41 for the maximum pressures which occur when the test section operating speed attains its maximum value. The pressures are shown for speeds of 100 and 50 fps for the small and large test sections, respectively, without a test body.

XVIII. ACKNOWLEDGMENTS

The authors are indebted to the following for their many contributions to the study and to this report:

Mr. W. F. Brownell, representing the Naval Ship Research and Development Center in technical and contract liaison.

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Mr. E. G. Elguther of the Physical Planning and Design Department, University of Minnesota.

Mr. Karl F. Wikstrom, principal engineering assistant of the St. Anthony Falls Hydraulic Laboratory.

Mrs. Shirley Kii, editorial assistant of the St. Anthony Falls Hydraulic Laboratory.

LIST OF FIGURES

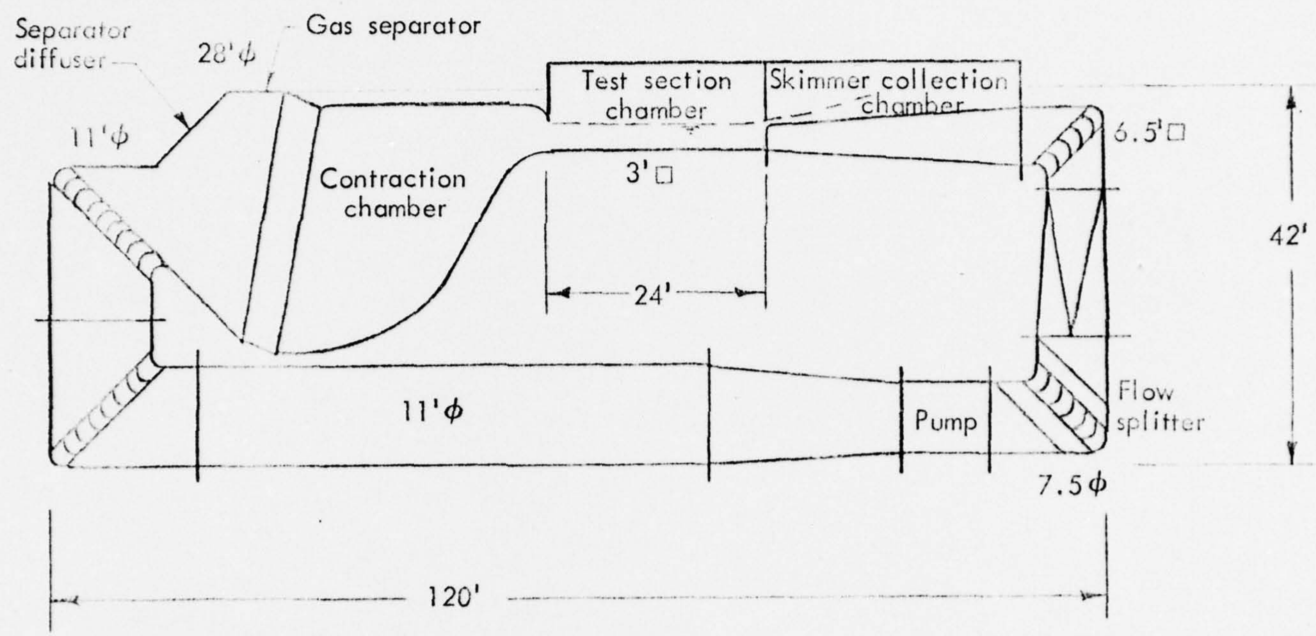


Fig. 1 - Schematic of Proposed 60 Knot Free Surface Channel (original version)

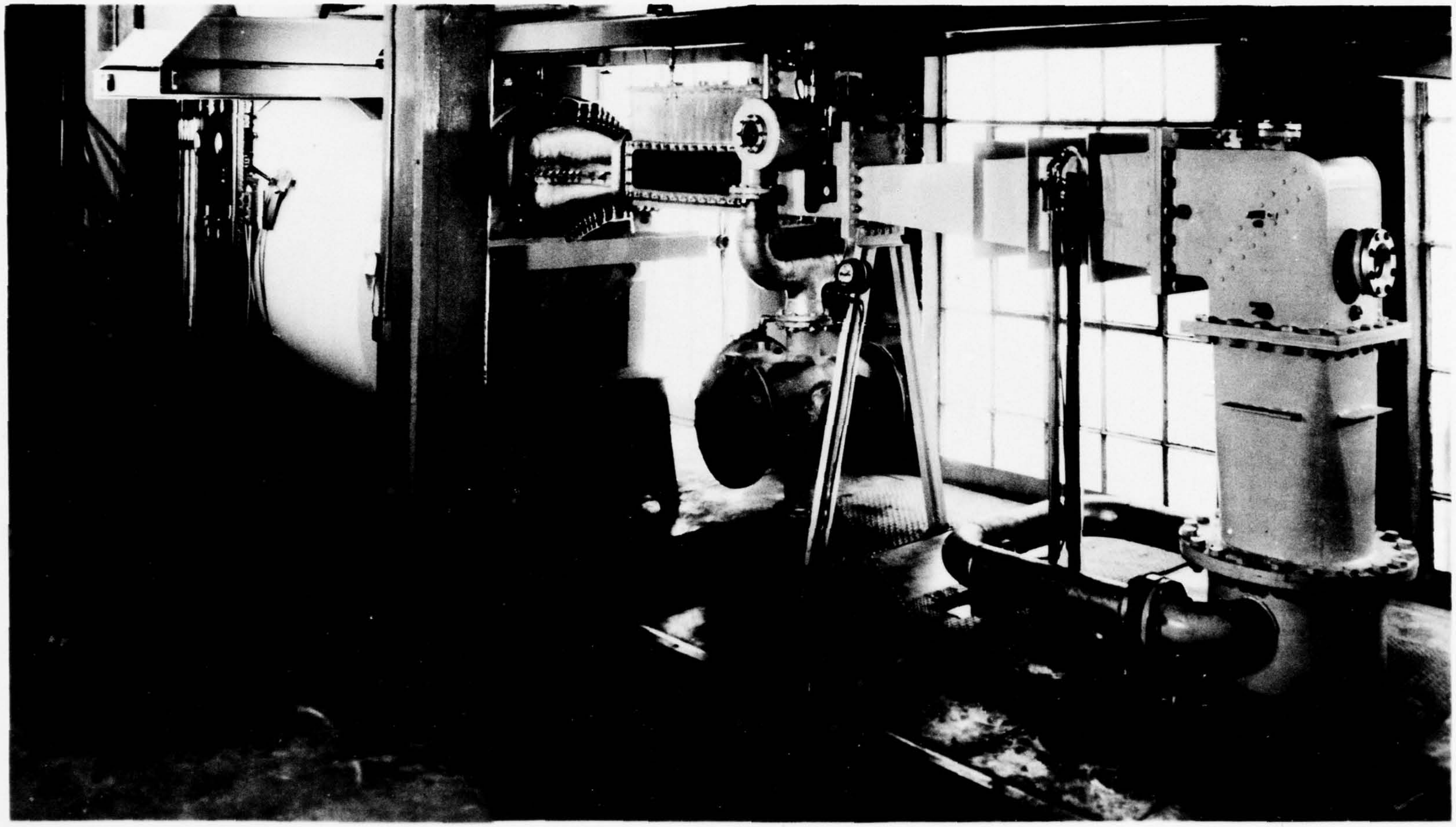


Fig. 2 - The 4.8 Scale Model employed in the tests at St. Anthony Falls

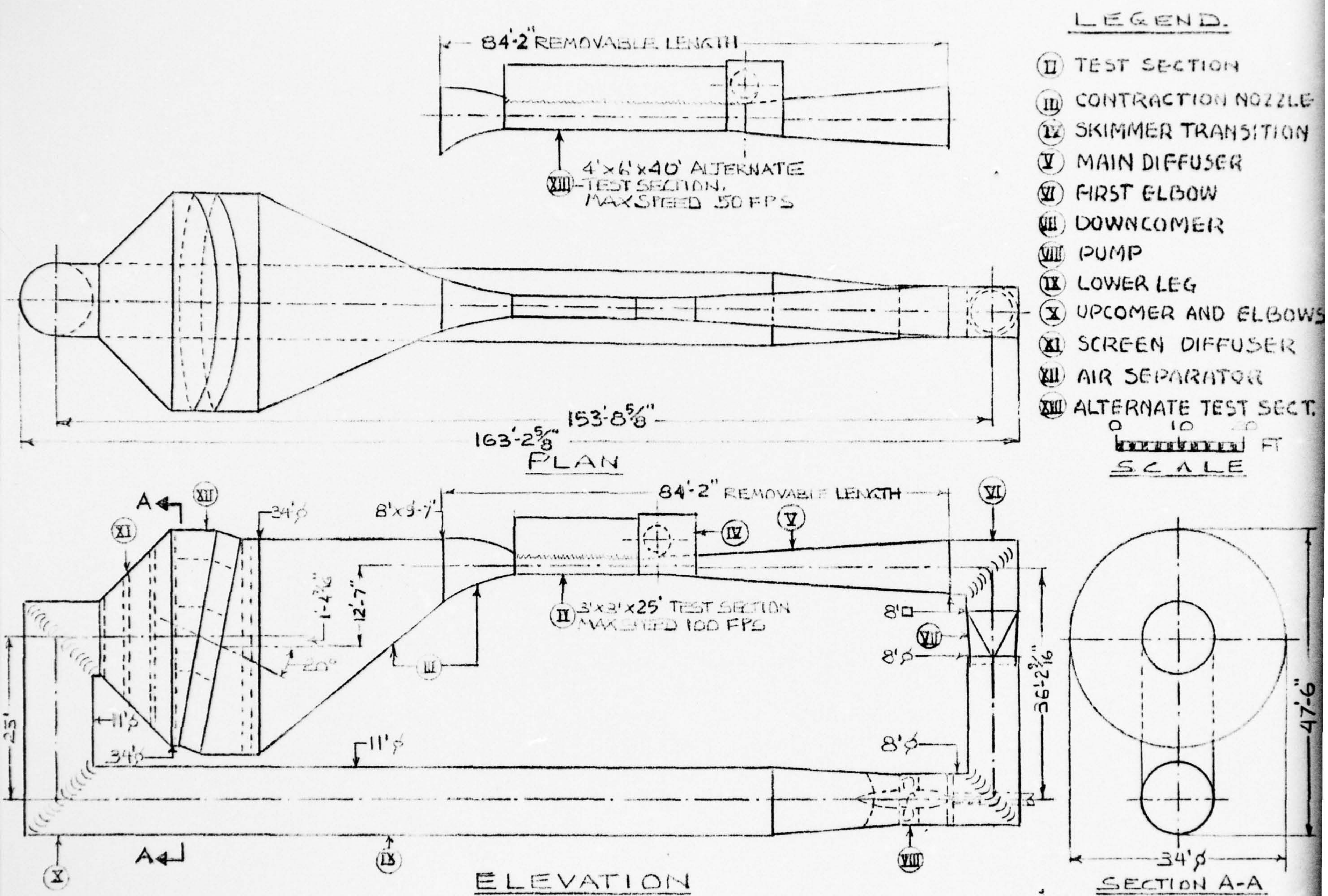


Fig. 3 - Proposed NSRDC High-Speed, Variable Pressure, Free Surface Test Facility

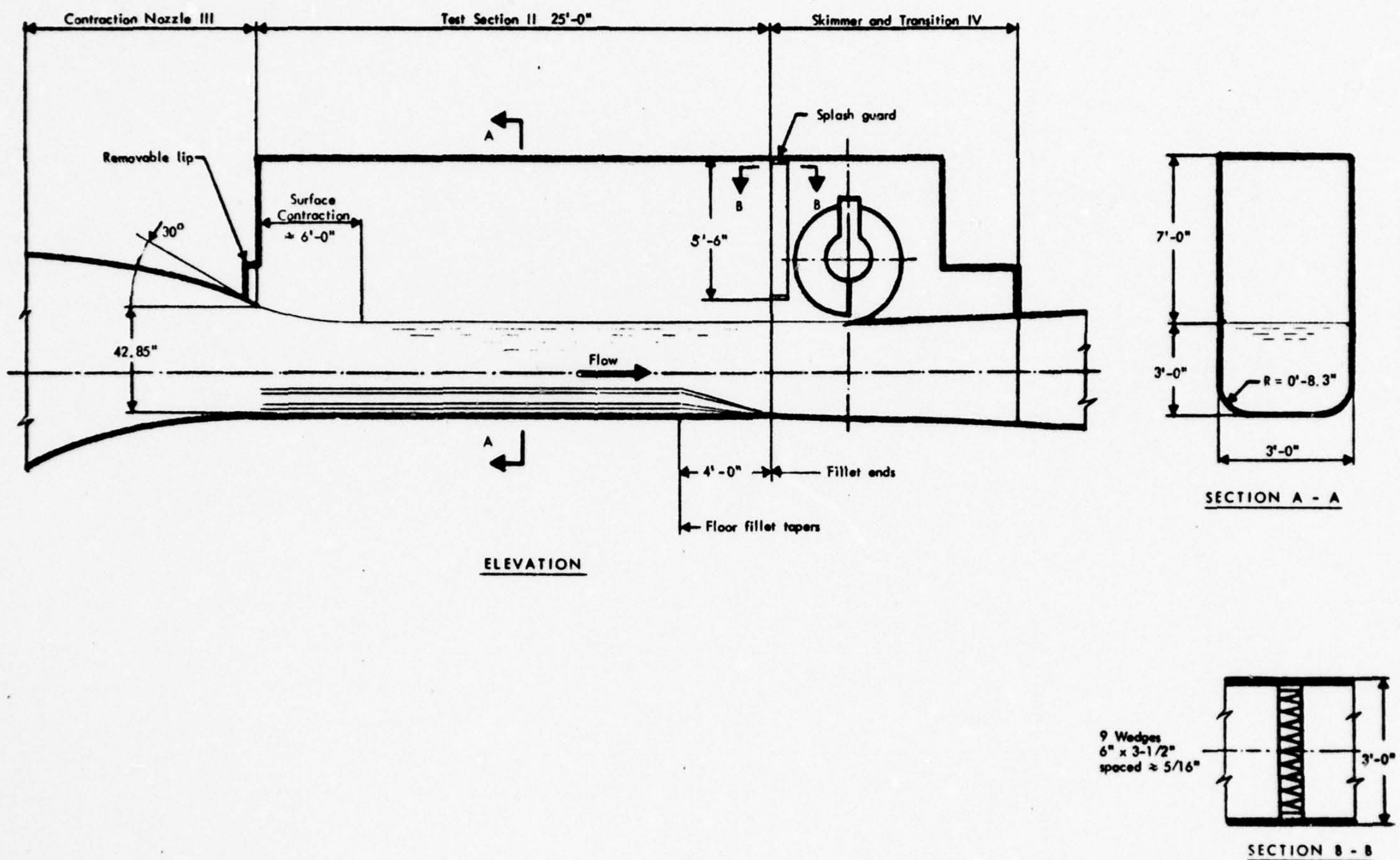
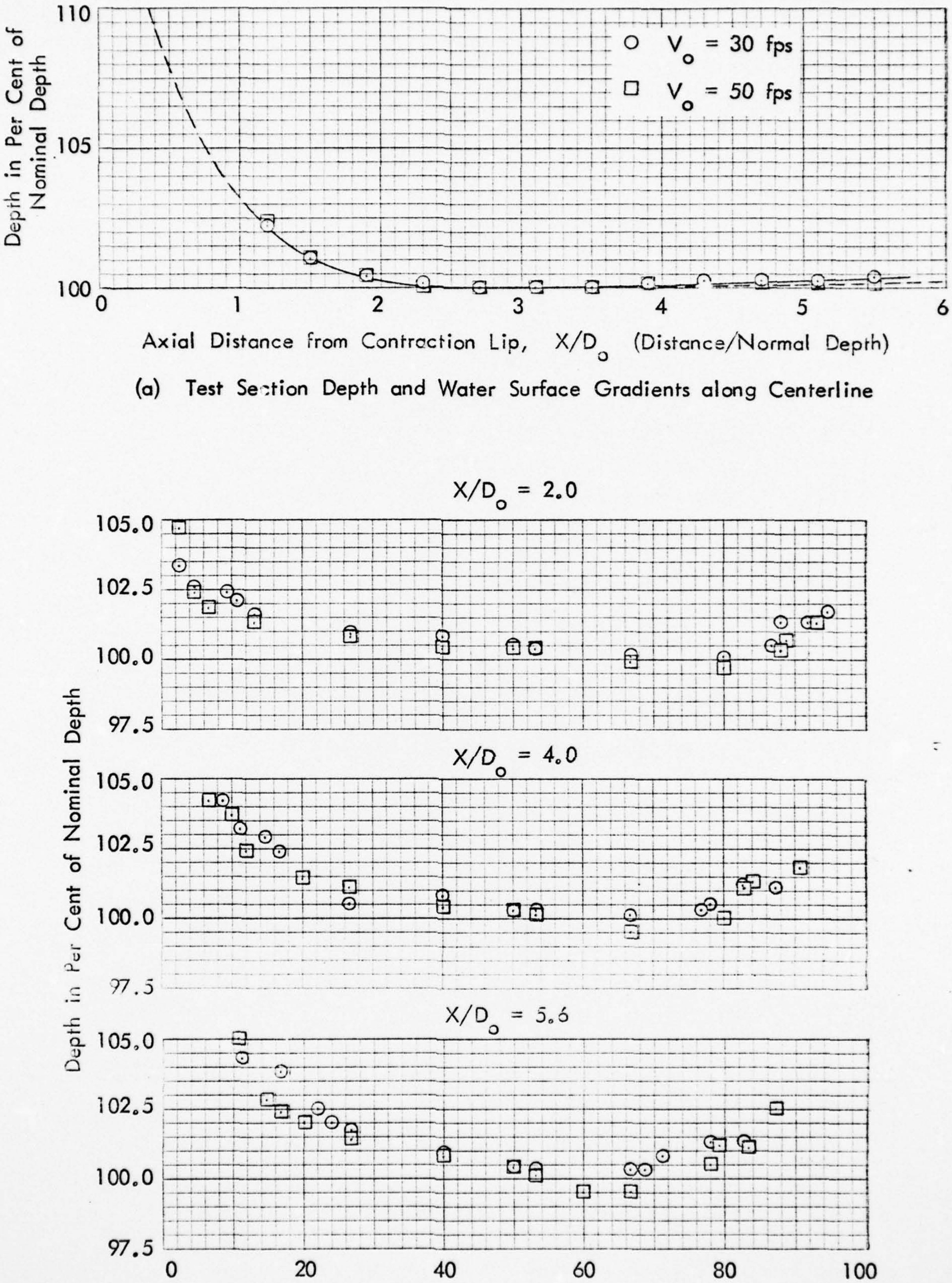


Fig. 4 - High-Speed Test Section Configuration (all dimensions relate to prototype inside flow surfaces)



(a) Test Section Depth and Water Surface Gradients along Centerline

(b) Lateral Surface Gradients

Fig. 5 - Water Surface Gradients

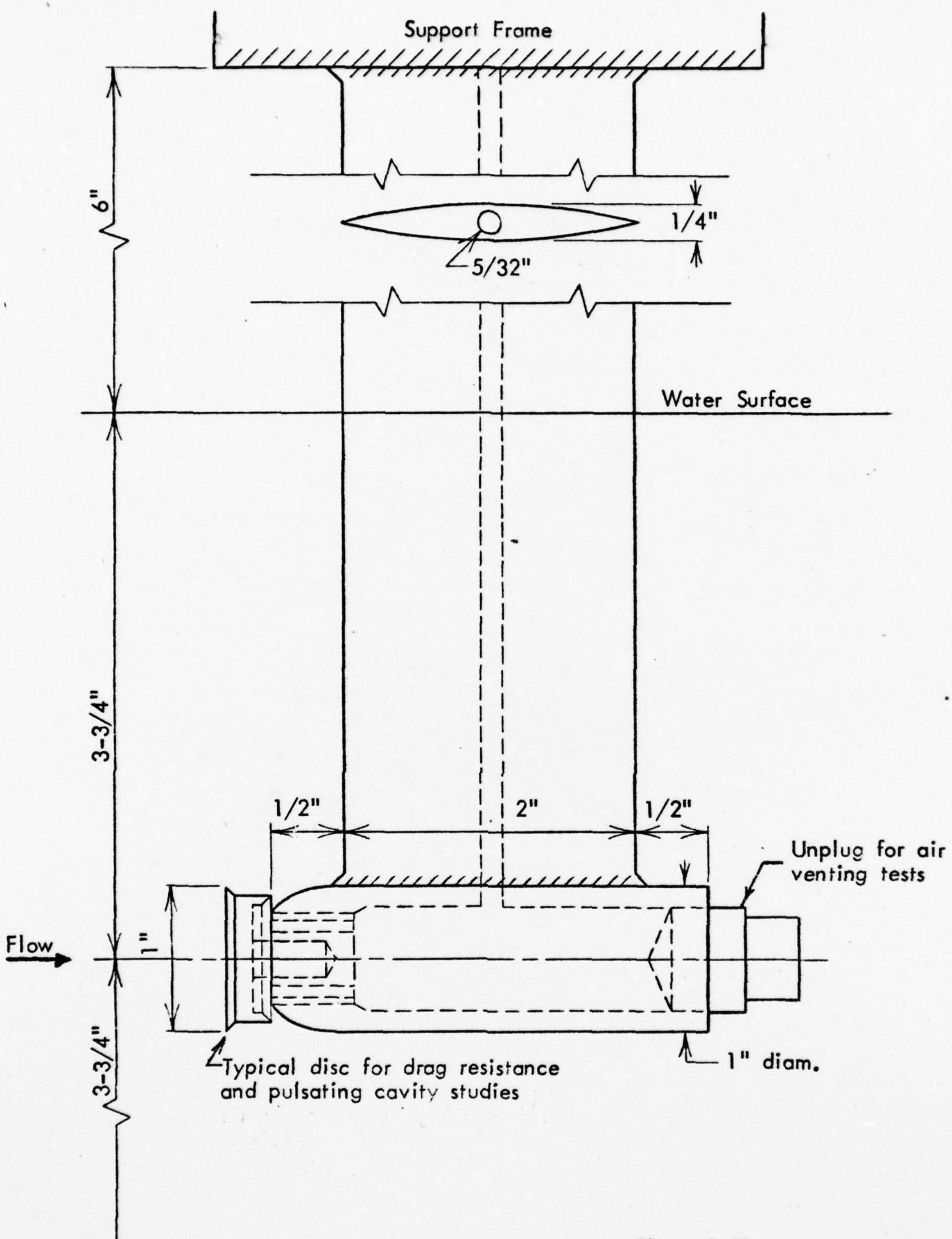


Fig. 6 - Test Bodies and Support System for the Model Channel

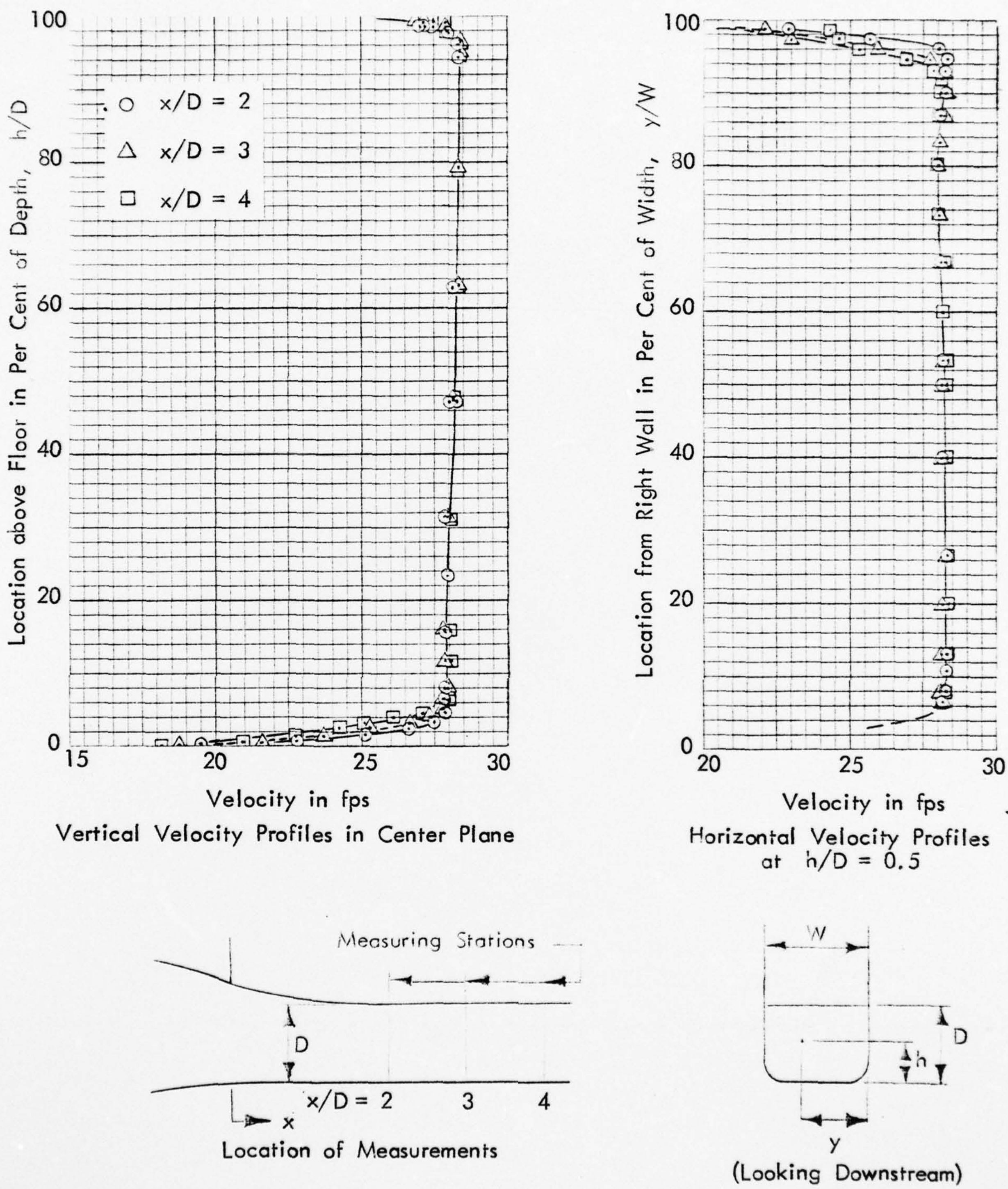


Fig. 7 - Test Section Velocity Profiles at V = 30 fps

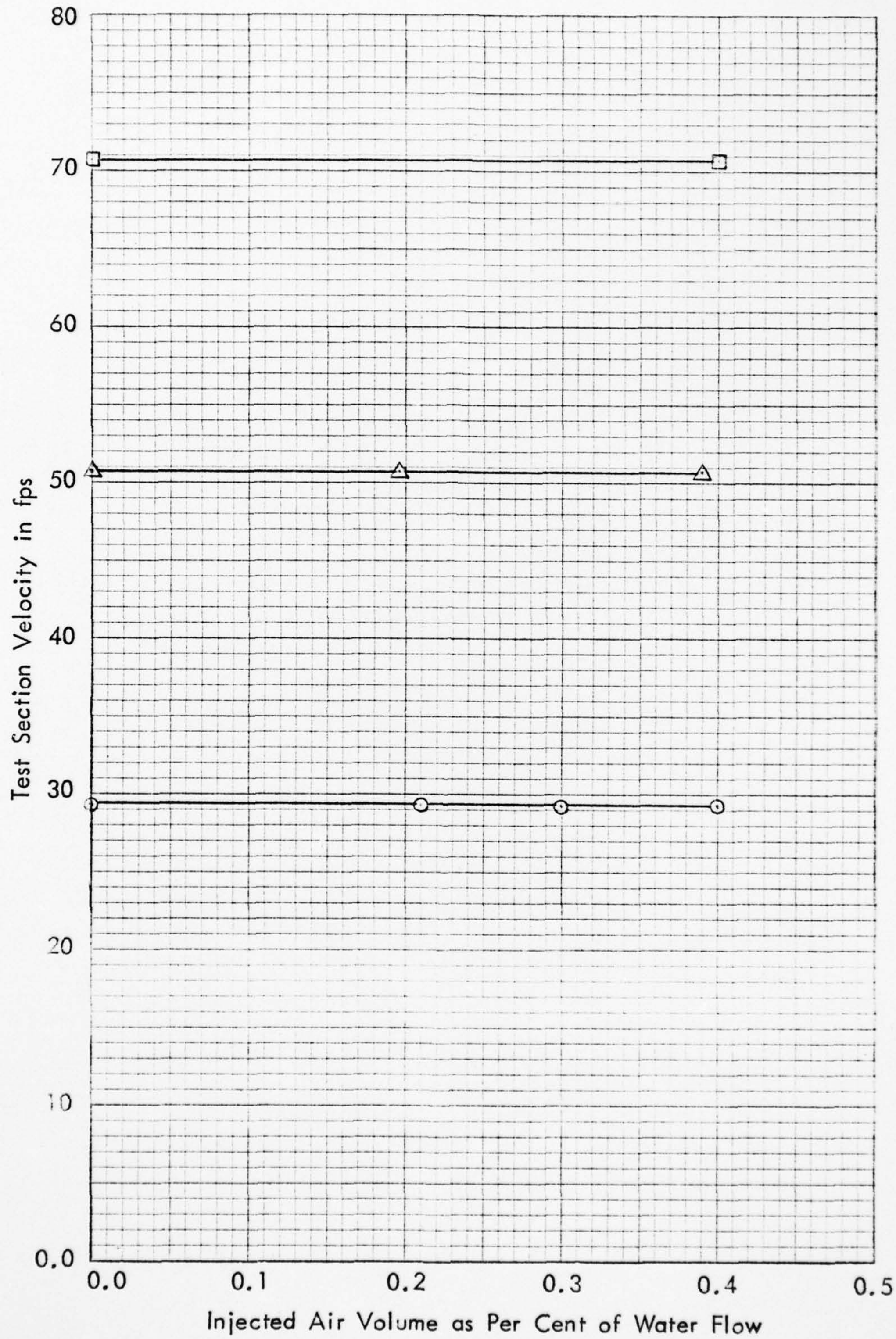


Fig. 8 - Influence of Injected Air on Test Section Velocity

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HYDRODYNAMIC STUDIES FOR A LARGE, HIGH-SPEED, VARIABLE PRESSURE--ETC(U)
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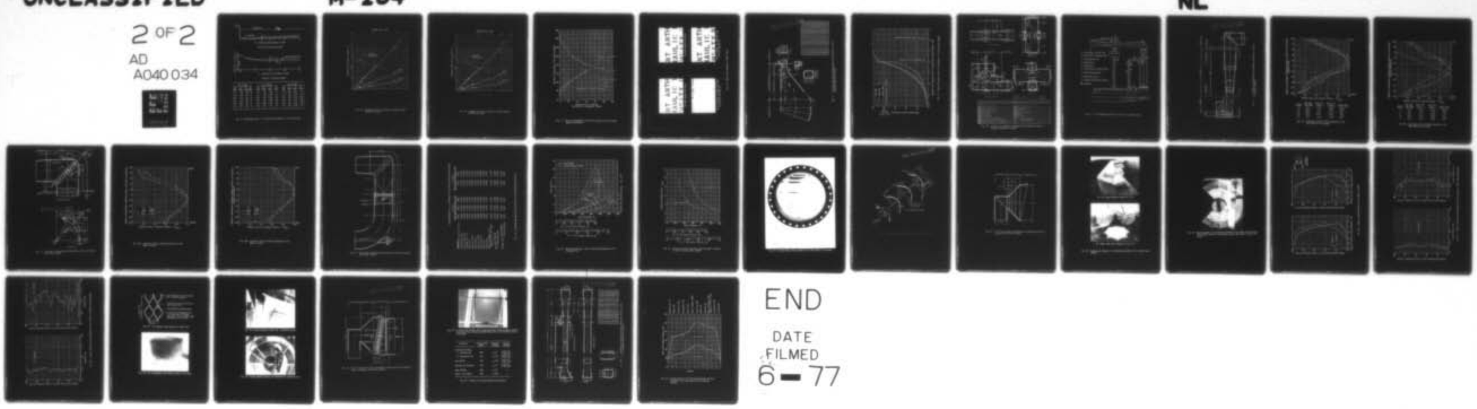

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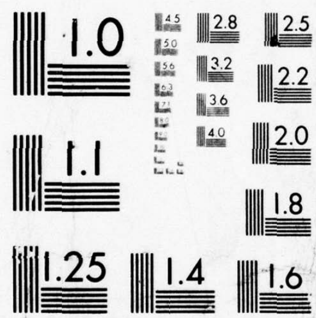
1.0
4.5
5.0
5.6
6.3
7.1
2.8
3.2
3.6
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2.5
2.2
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1.1
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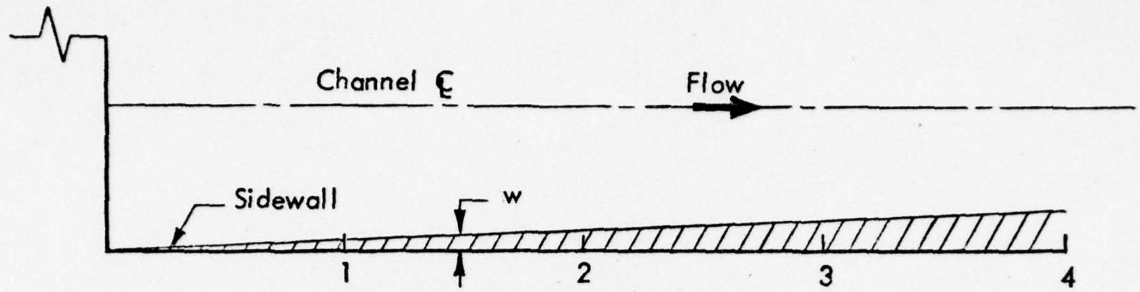
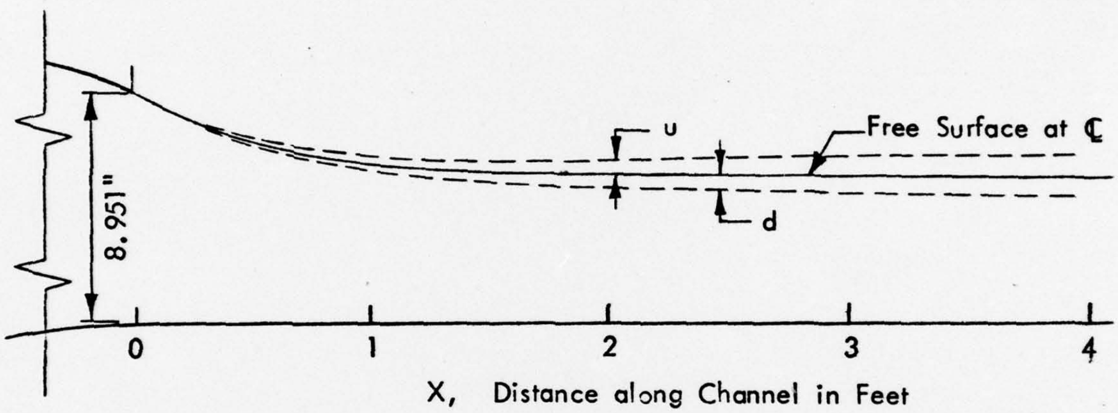
1.25
1.4
1.6



X, Distance along Channel in Feet

Plan View of Channel Surface



X, Distance along Channel in Feet

Elevation of Channel Surface

V = 15 fps				V = 30 fps				V = 50 fps			
X (ft)	w (in.)	u (in.)	d (in.)	X (ft)	w (in.)	u (in.)	d (in.)	X (ft)	w (in.)	u (in.)	d (in.)
1.0	.35	.68	0	1.0	.25	.86	0	1.0	.25	1.01	0
1.5	.52	.69	0	1.5	.44	1.02	.10	1.5	.38	1.24	.10
2.0	.70	.66	0	2.0	.62	1.06	.20	2.0	.50	1.44	.25
2.5	.87	.66	0	2.5	.81	1.09	.24	2.5	.63	1.55	.34
3.0	1.04	.66	0	3.0	1.00	1.10	.35	3.0	.75	1.64	.45
3.5	1.21	.66	0	3.5	1.12	1.13	.47	3.5	.88	1.70	.56

Fig. 9 - Dimensional Extent of the Sidewall Disturbances of the Free Surface

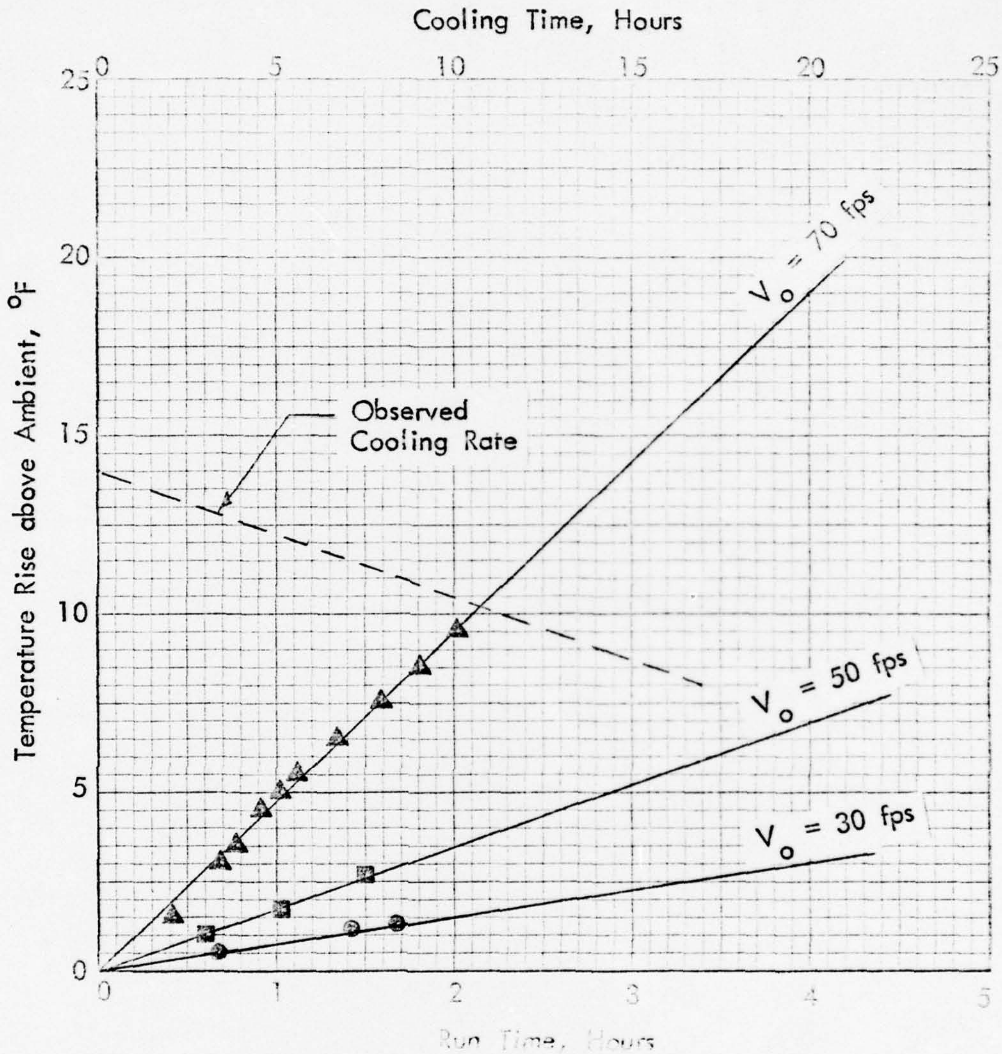


Fig. 10 - Temperature Rise and Cooling for Model Channel (without test body)

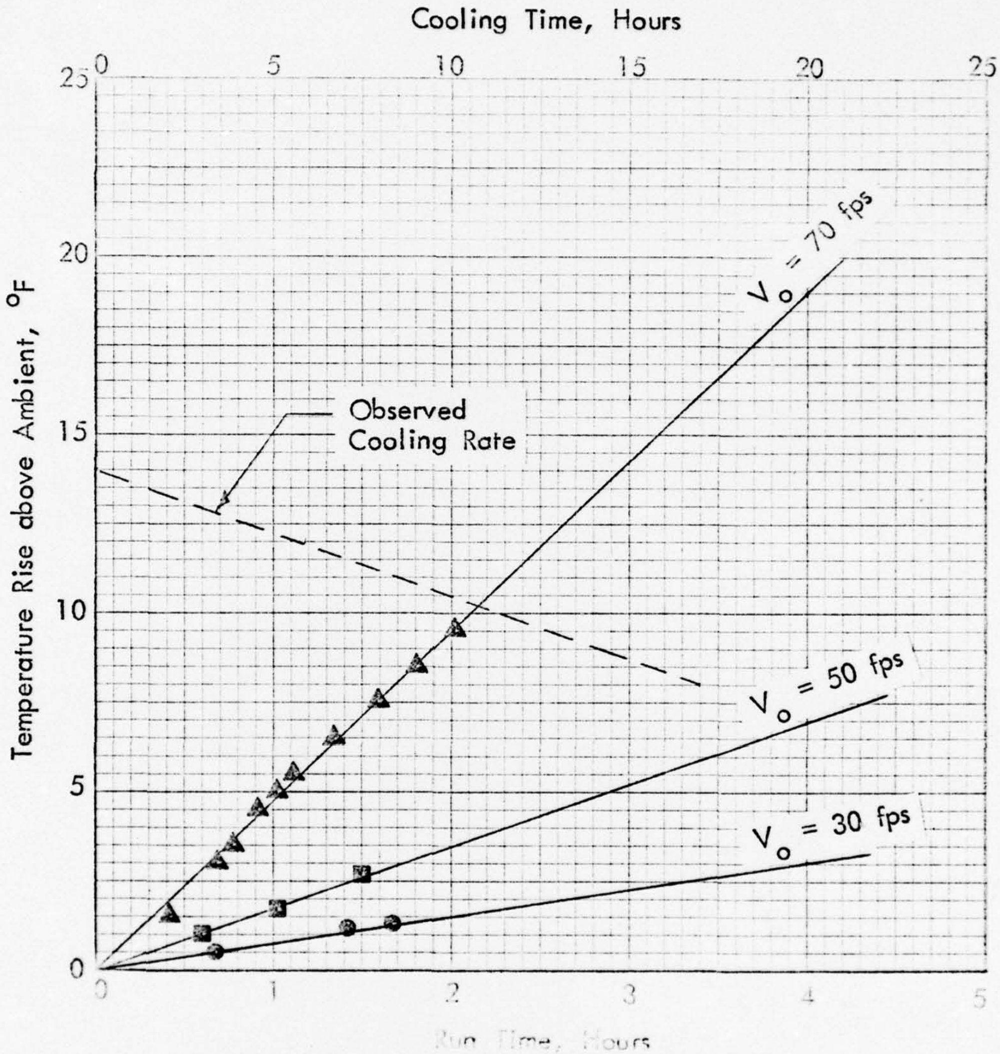


Fig. 10 - Temperature Rise and Cooling for Model Channel (without test body)

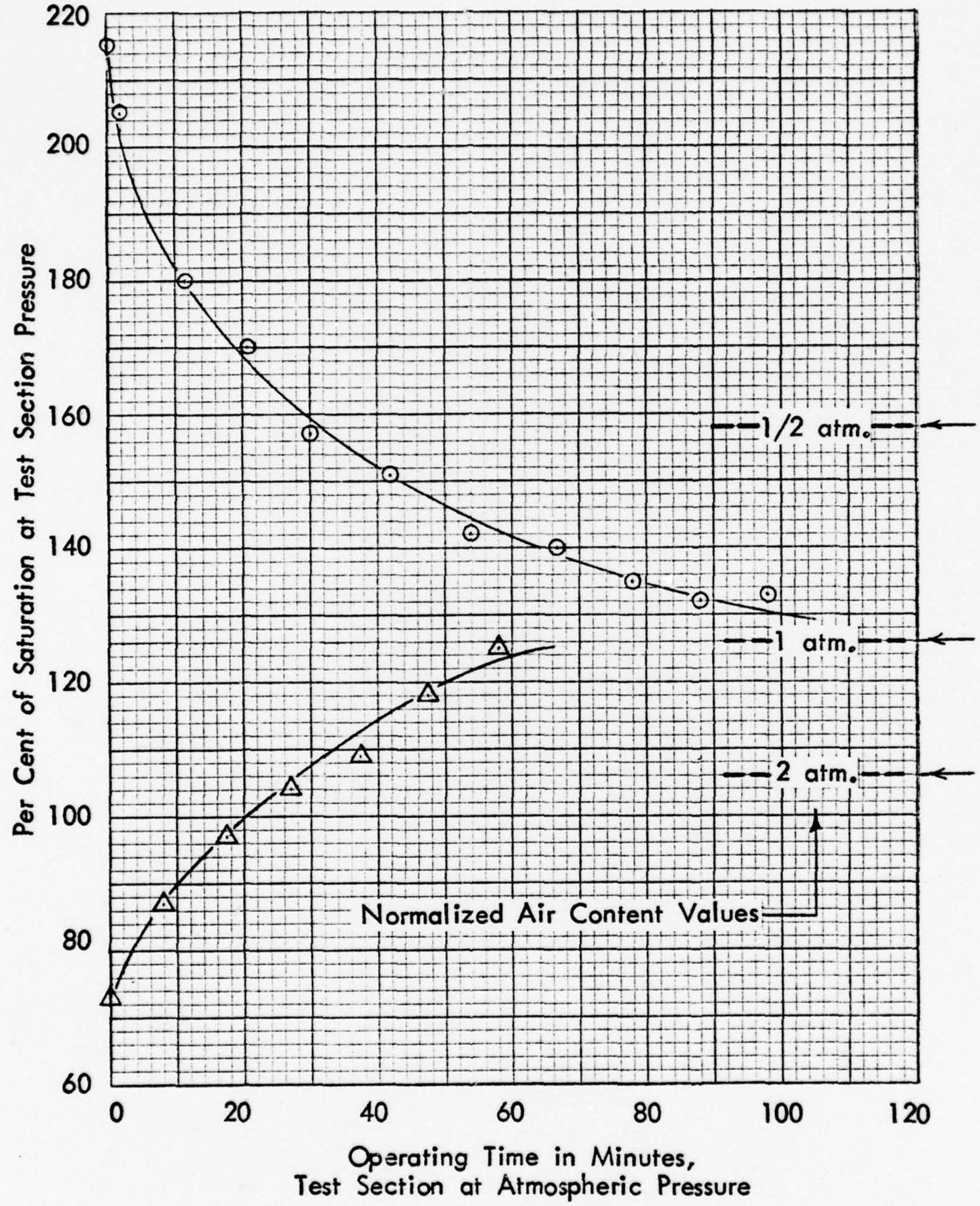
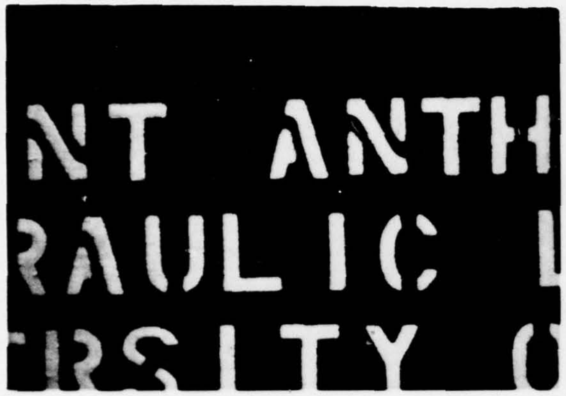
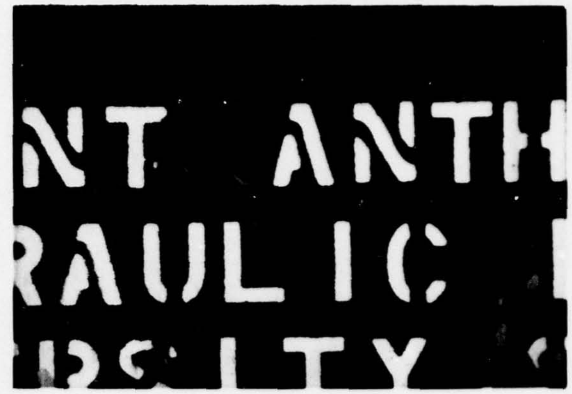


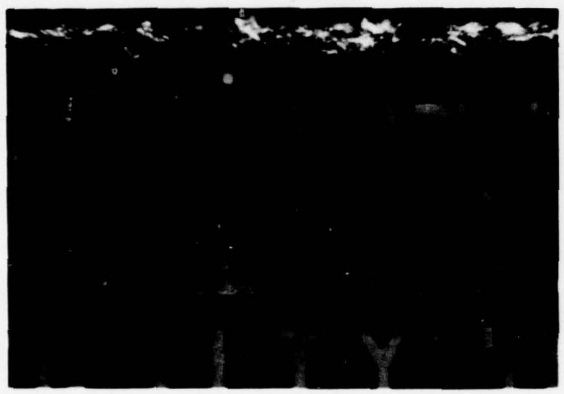
Fig. 11 - Rate of Normalization of Total Gas Content for Free Surface Operating Conditions



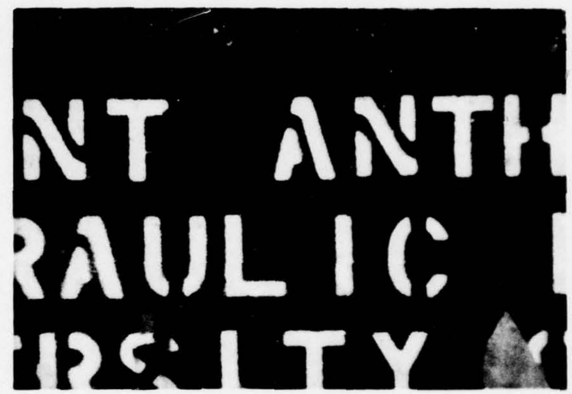
(a) With Settled Still Water



(c) With Settled Still Water

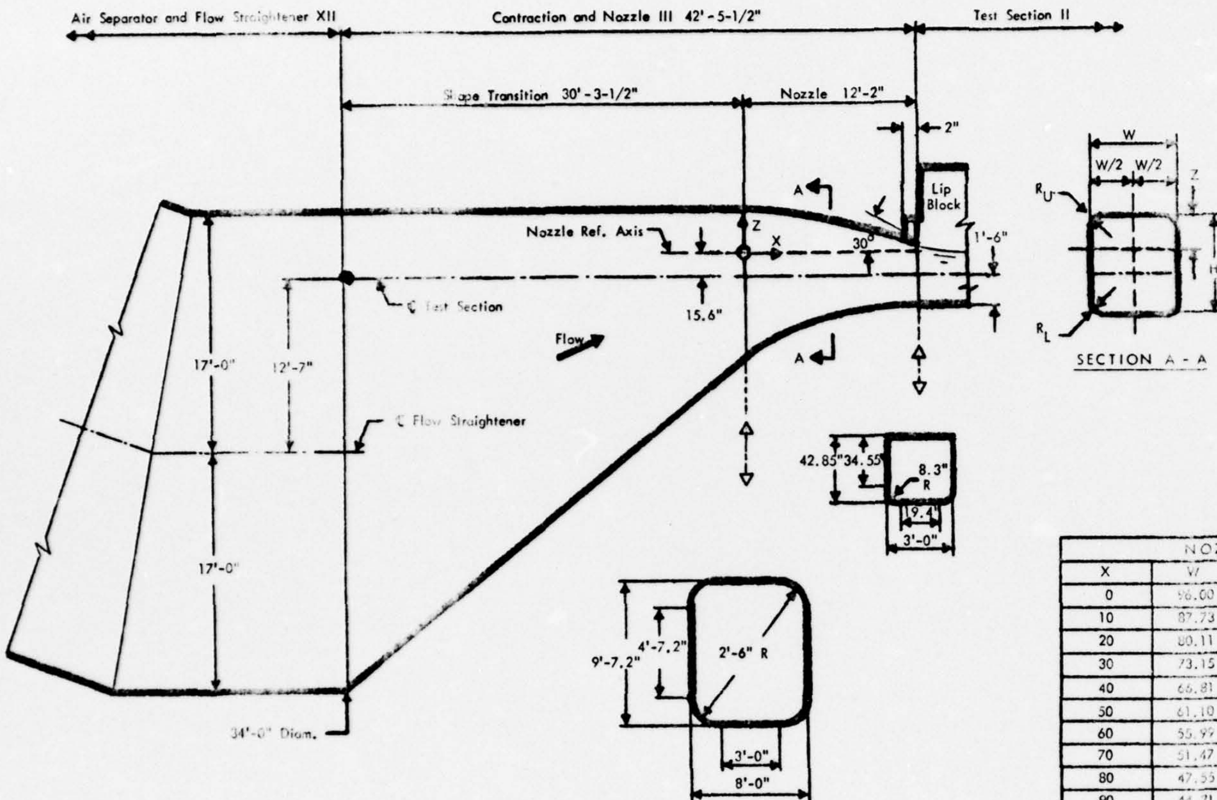


(b) V = 70 fps, p = atm and with 0.4 per cent Injected Air



(d) V = 70 fps, p = 0.2 atm and with No Injected Air

Fig. 12 - Effect of Air Bubbles on Water Clarity



NOZZLE DIMENSIONS - INCHES					
X	W	H	R_U	R_L	Z
0	96.00	115.20	30.00	30.00	37.32
10	87.73	107.80	25.86	26.49	37.31
20	80.11	101.44	22.06	23.31	37.24
30	73.15	95.85	18.57	20.45	37.06
40	66.81	90.82	15.41	17.91	36.72
50	61.10	86.18	12.55	15.67	36.16
60	55.99	81.82	9.99	13.74	35.31
70	51.47	77.61	7.74	12.11	34.13
80	47.55	73.47	5.78	10.78	32.56
90	44.21	69.30	4.11	9.73	30.55
100	41.44	65.03	2.72	8.97	28.03
110	39.25	60.58	1.62	8.50	24.96
120	37.62	55.88	0.81	8.30	21.28
130	36.55	50.86	0.28	8.30	16.92
140	36.05	45.47	0.02	8.30	11.85
144	36.00	43.20	0	8.30	9.60
144.6	36.00	42.85	0	8.30	9.25

Fig. 13 - Contraction and Nozzle Configuration (all dimensions relate to prototype inside flow surfaces)

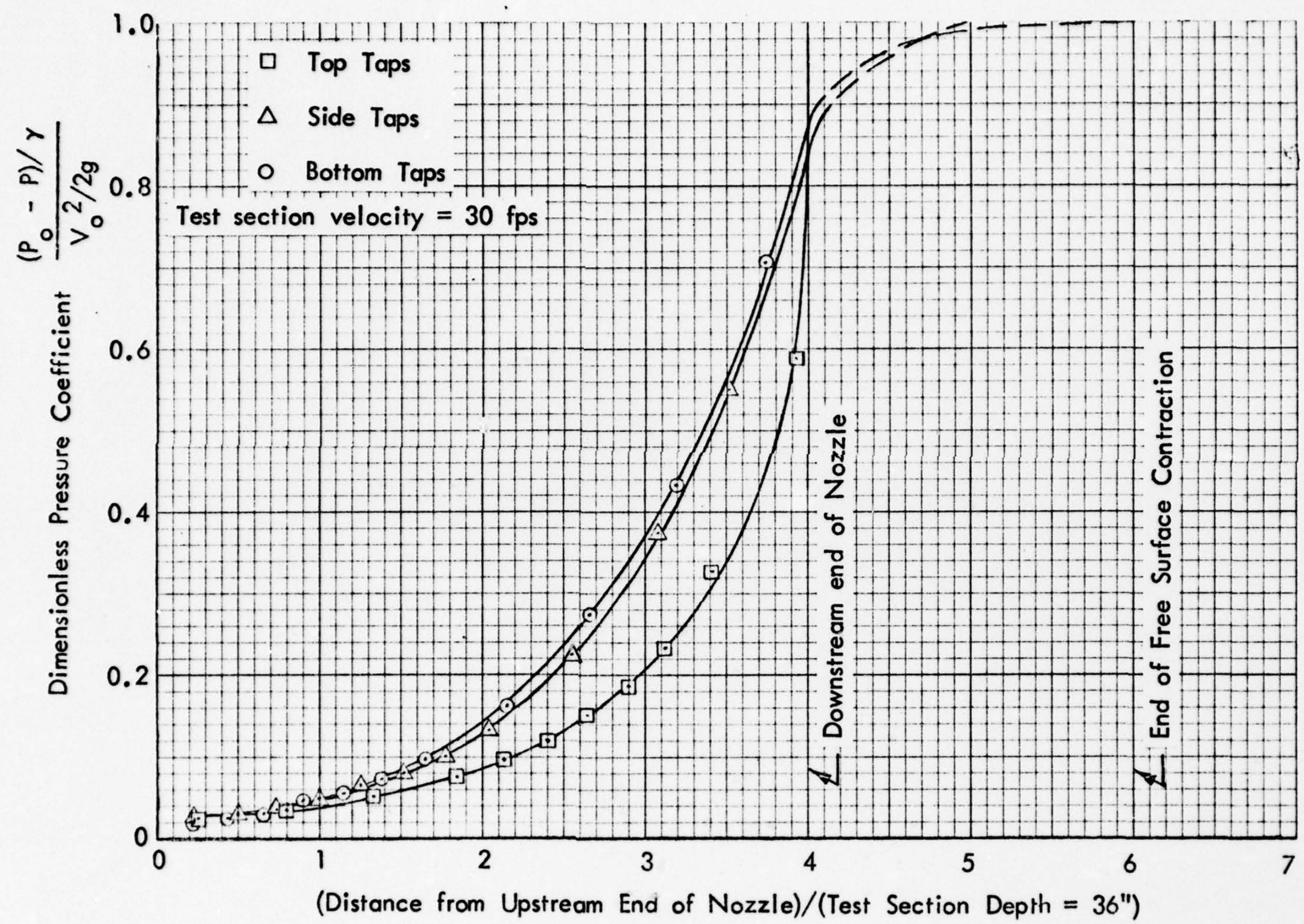
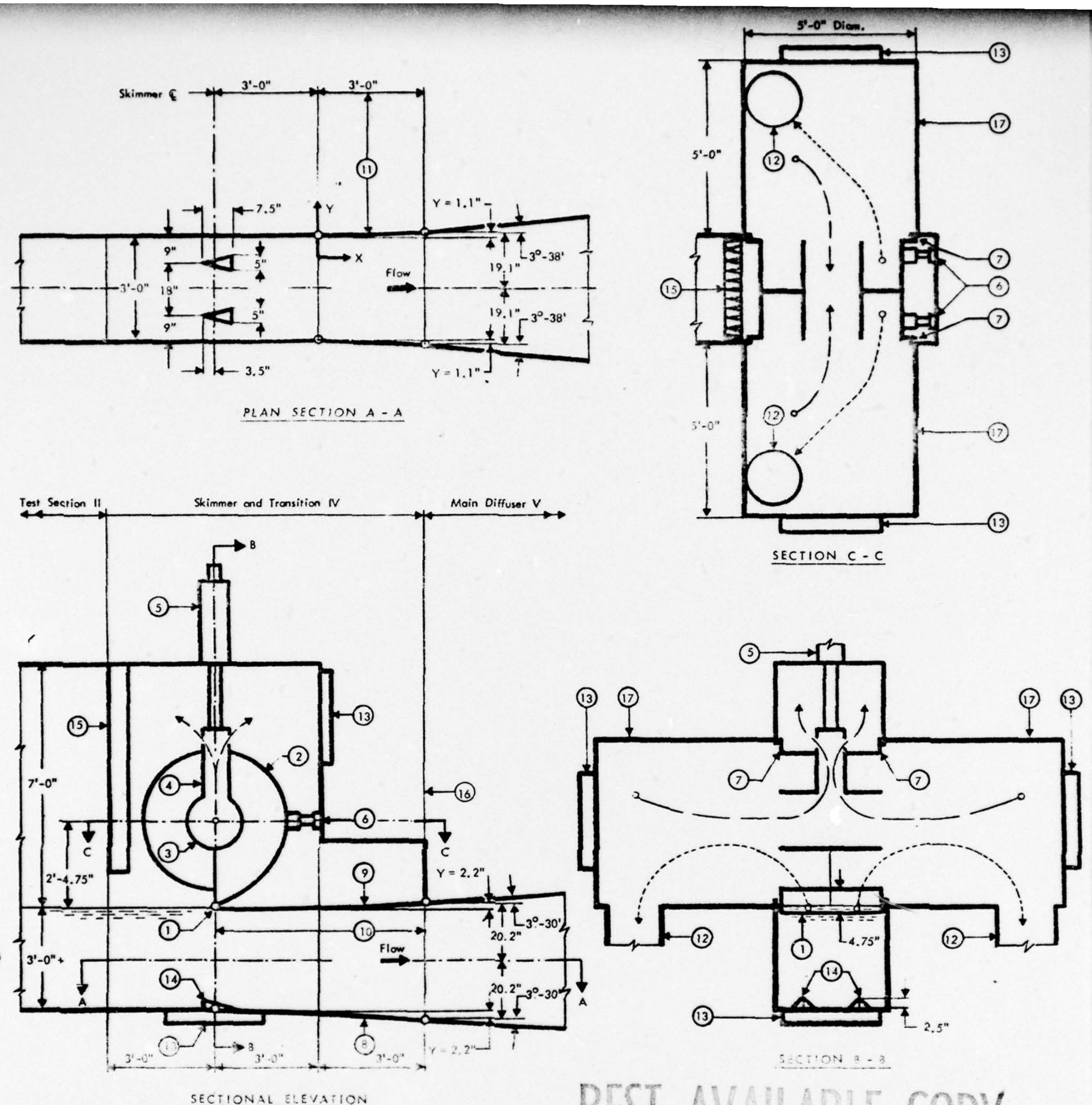


Fig. 14 - Pressure Gradients along the Boundaries of the Contraction Nozzle



KEY			
1	Adjustable Skimmer Lip (height 3' ± 2.5 in.)	11	Wall Transition (both walls $Y = 0.0009494\ X^2$ in.)
2	Skimmer Housing (48 in. diam.)	12	Discharge to Skimmer Pump (≈8 in. pipe)
3	Skimmer Air Flue (≈20 in. diam.)	13	Viewing Window (6 in. diam.)
4	*Skimmer Air Chimney* (≈6 in. diam.)	14	Vortex Generators (2)
5	Skimmer Adjusting Mechanism	15	Splash Guard (see Section II-F-7)
6	Skimmer Jack Screw	16	Break Plane
7	Skimmer Sealing Flanges	17	Separator Chamber
8	Floor Transition (curve $Y = 0.0004247\ X^2$ in.)		— — —▶ Route of Skimmed Air
9	Flexible Roof Transition (normal curve $Y = 0.0004247\ X^2$ in.)		- - - - -▶ Route of Skimmed Water
10	Extent of Floor and Roof Transition Curves with Origins at Left		

Fig. 15 - Skimmer and Transition Configuration (all dimensions relate to prototype inside flow surfaces)

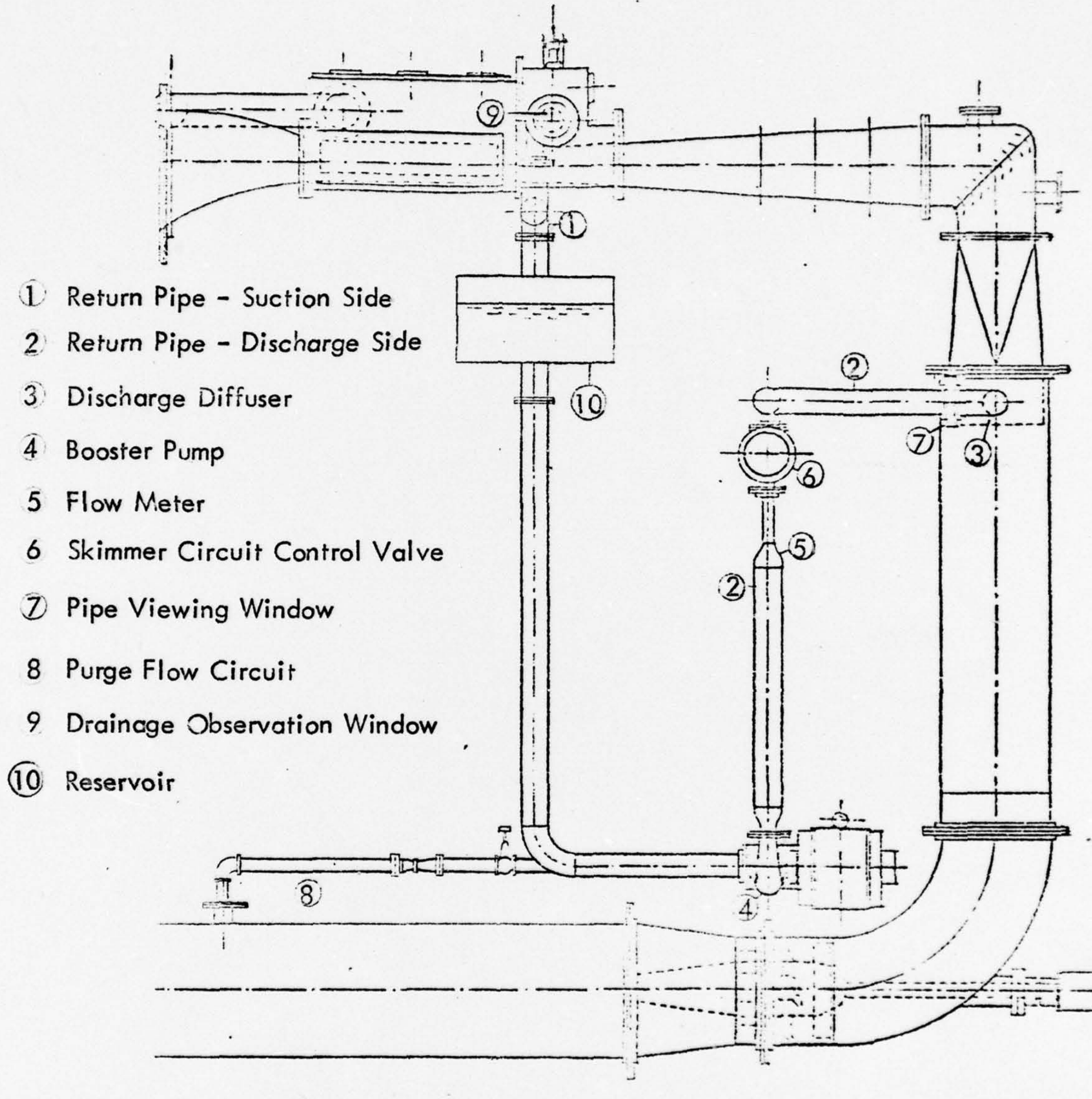


Fig. 16 - The Skimmed Flow Return System for the Model Studies

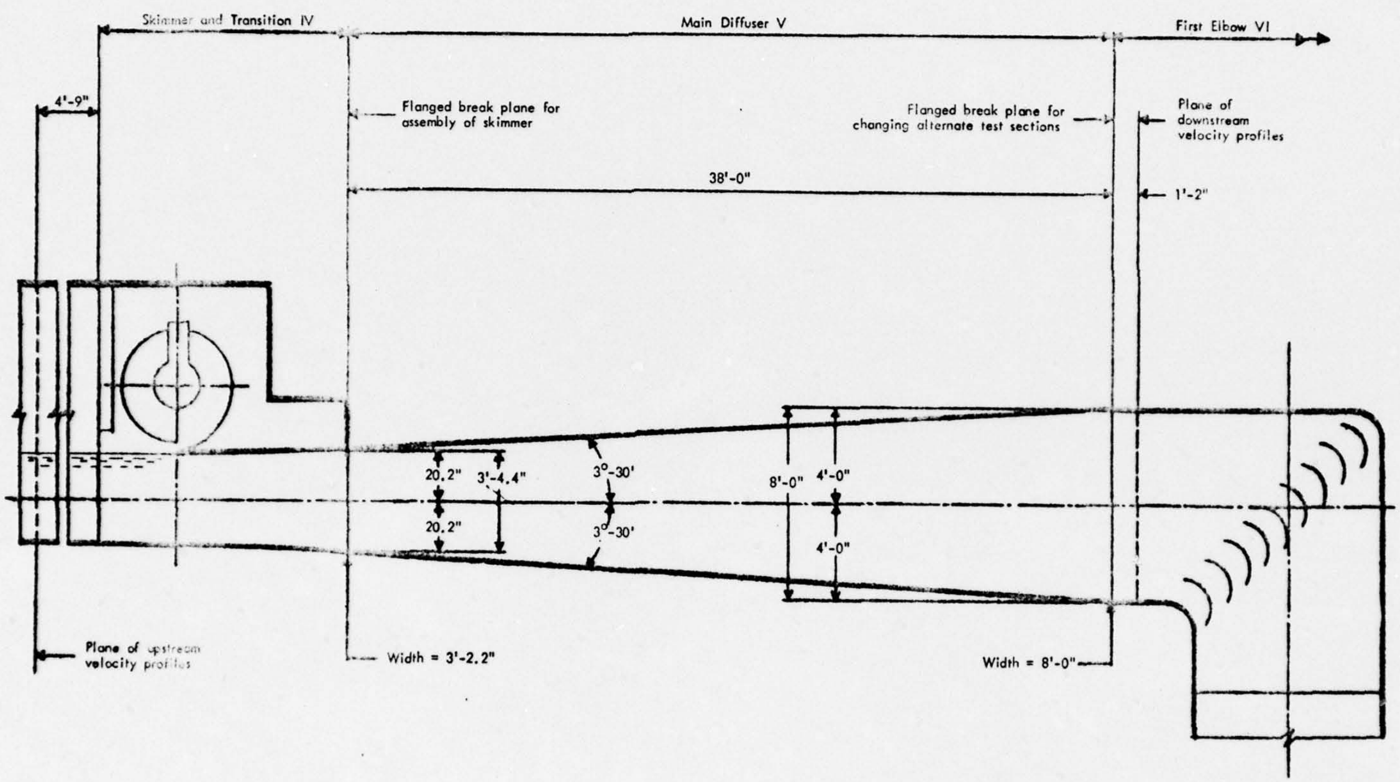
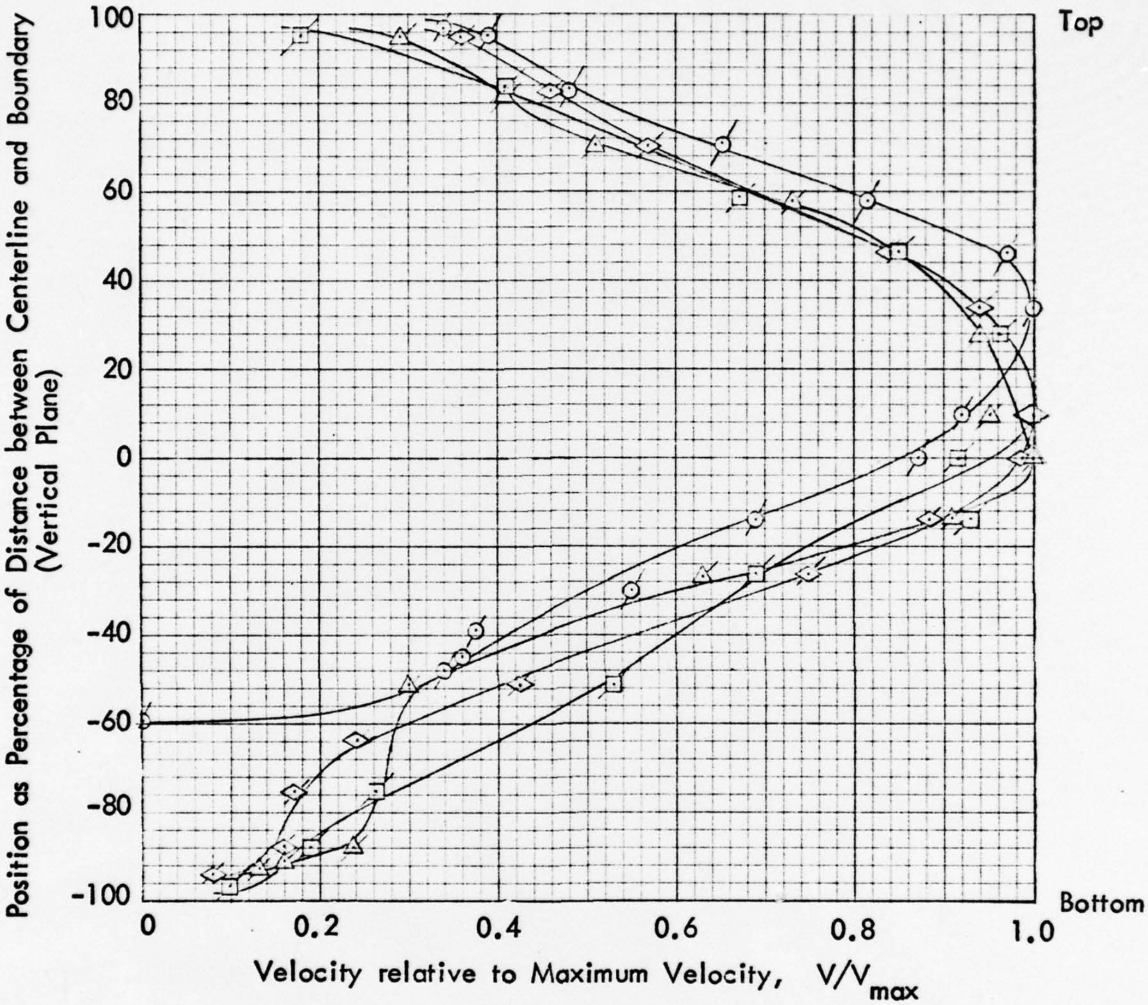
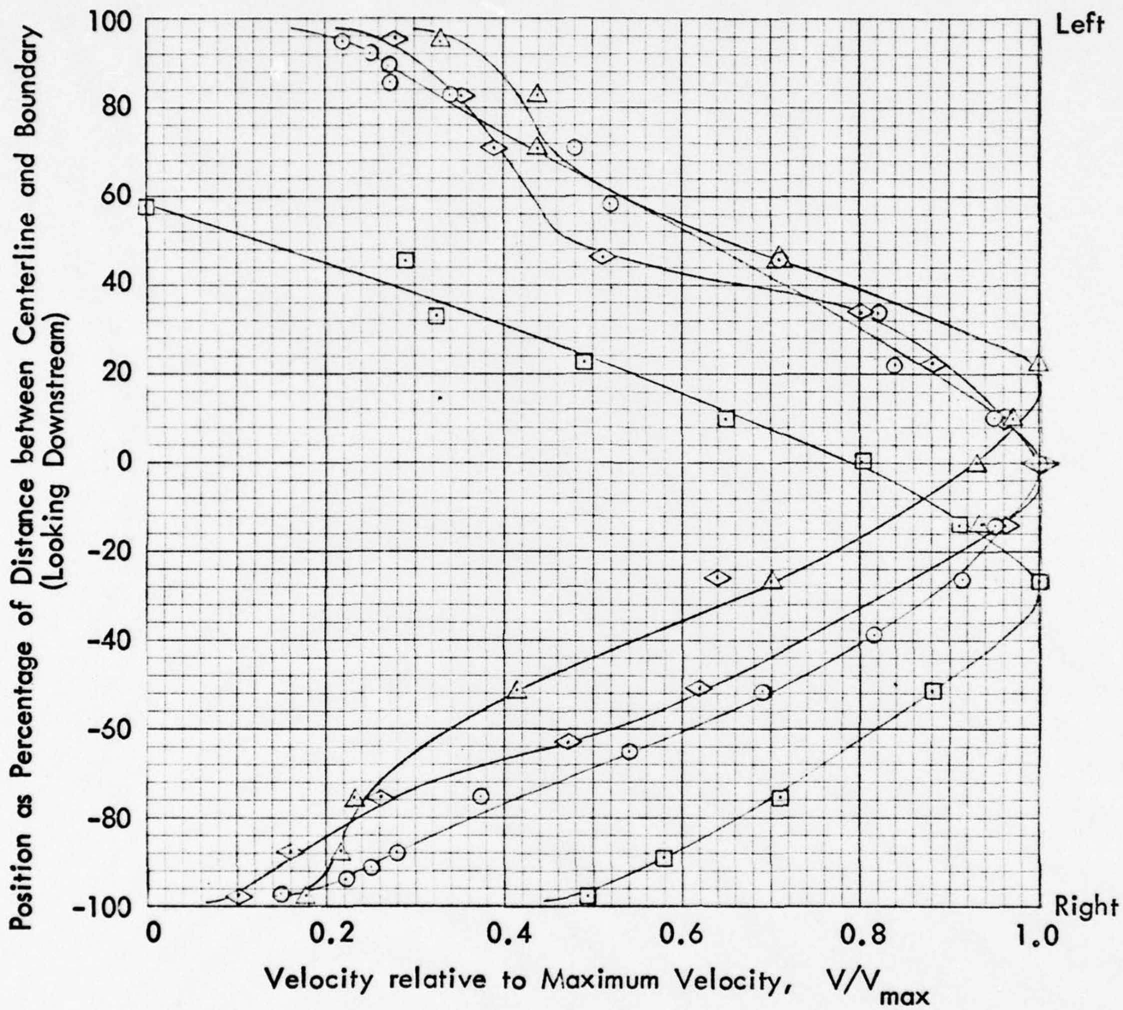


Fig. 17 - Main Diffuser Configuration (all dimensions relate to prototype inside flow surfaces)



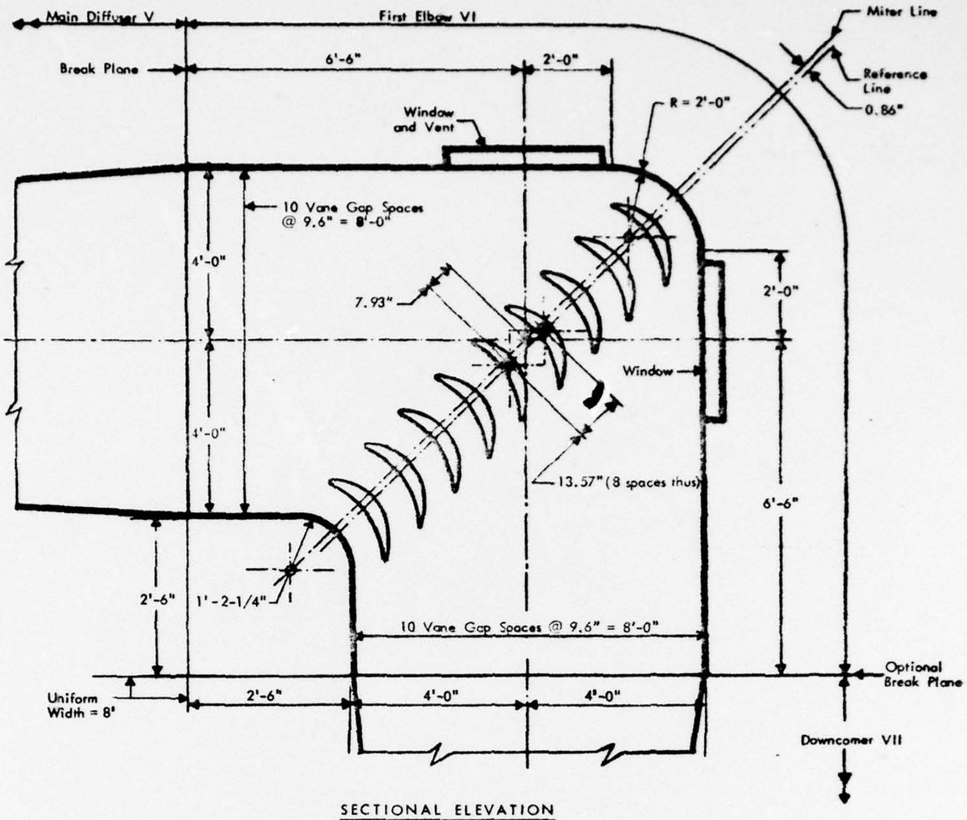
Symbol	Test Sect. Vel. (fps)	Mean Vel. (fps)	Max. Vel. (fps)	Vortex Gen.
⌀ (circle)	27.6	5.65	14.82	None
△ (triangle)	28.0	5.73	13.77	1/2"
◇ (diamond)	50.0	10.24	24.61	1/2"
□ (square)	27.6	5.65	11.44	3/4"

Fig. 18a - Centerline Velocity Profiles Downstream of the Main Diffuser in the Model



Symbol	Test Sect. Vel. (fps)	Mean Vel. (fps)	Max. Vel. (fps)	Vortex Gen.
○	27.8	5.69	12.78	None
△	28.1	5.75	13.23	1/2"
◇	49.6	10.16	23.82	1/2"
□	27.6	5.65	14.03	3/4"

Fig. 18b - Centerline Velocity Profiles Downstream of the Main Diffuser in the Model



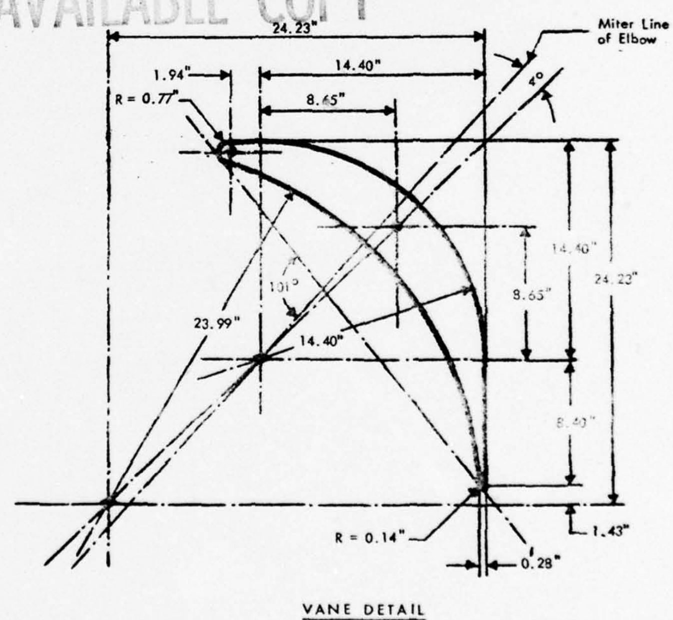


Fig. 19 - First Elbow Configuration (all dimensions relate to prototype inside flow surfaces)

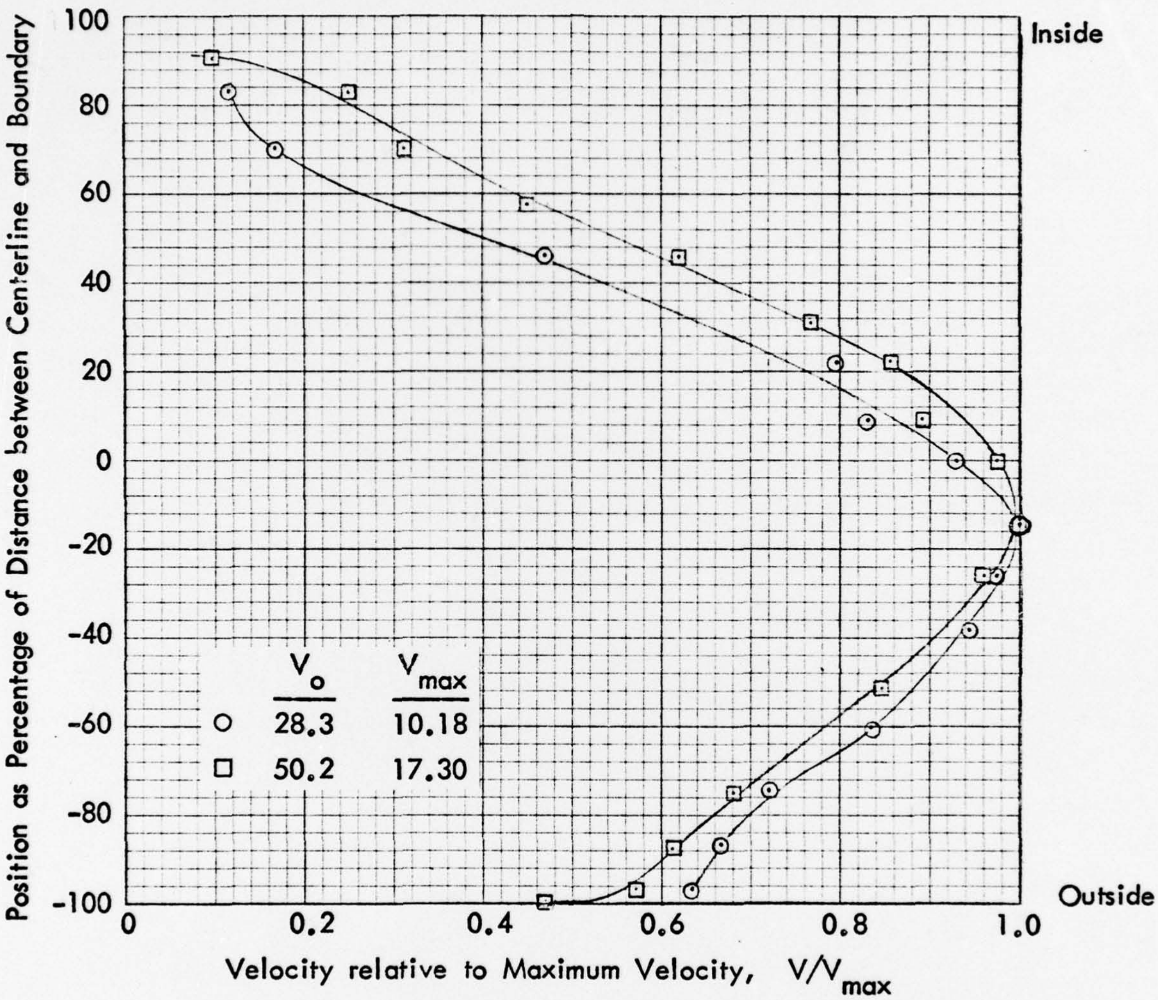


Fig. 20a - Centerline Velocity Profiles Downstream of First Elbow of Model

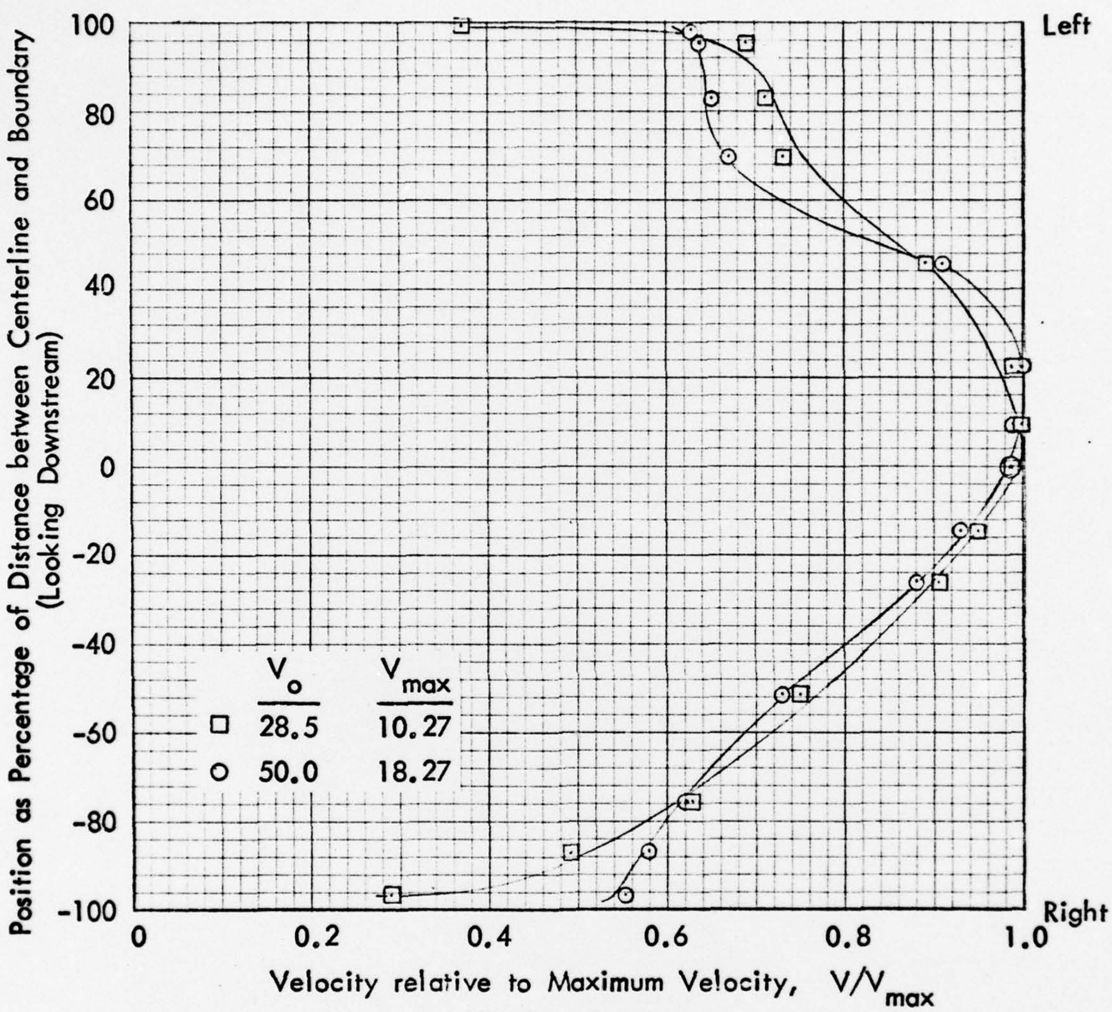


Fig. 20b - Centerline Velocity Profiles Downstream of First Elbow of Model

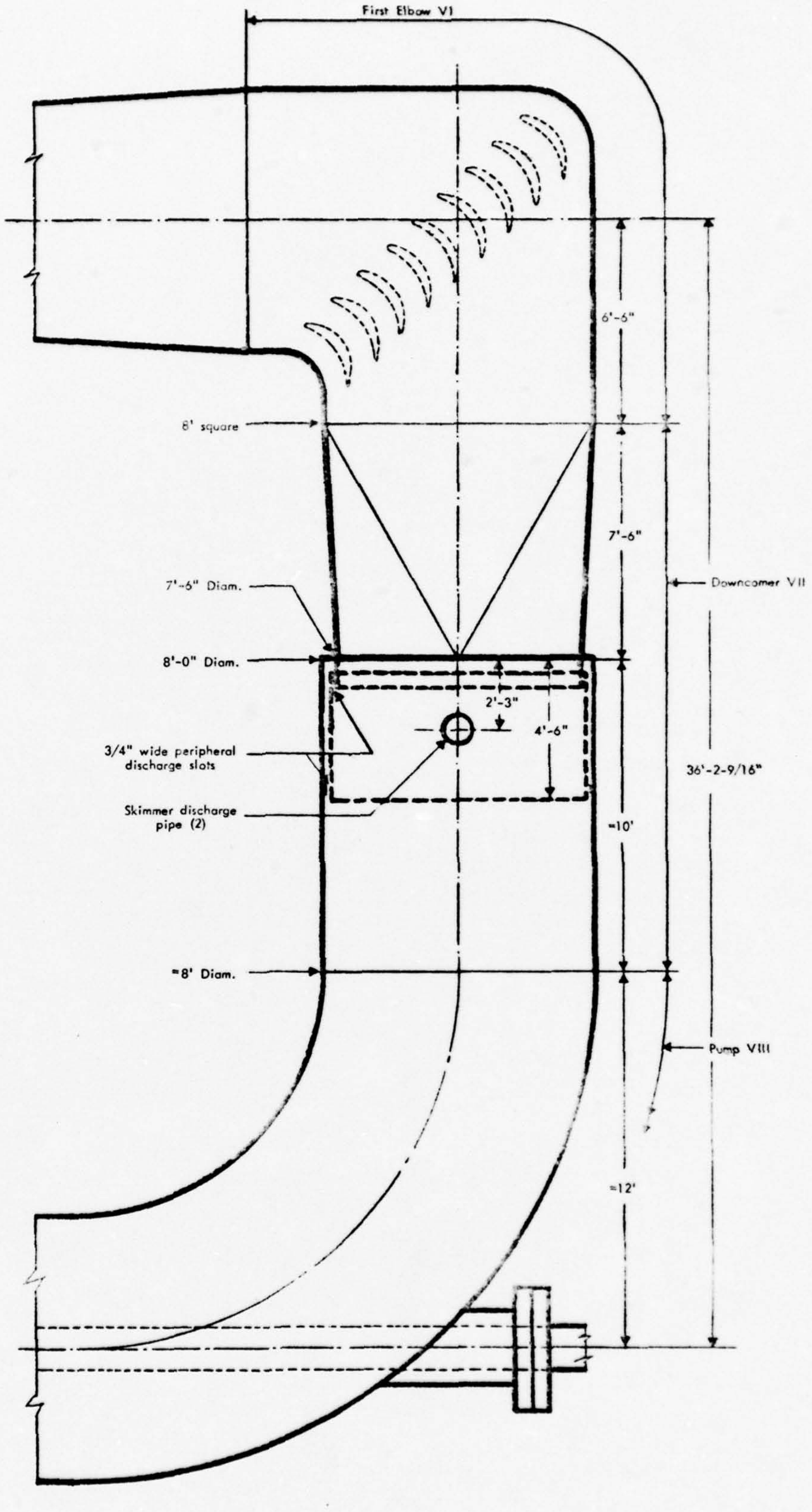


Fig. 21 - Downcomer Configuration (all dimensions relate to prototype inside flow surfaces)

Loss Expressed as K_o Multiples of the Test Section Velocity Head

Component	3' by 3' Test Section Velocity, fps			6' by 4' Test Section Velocity, fps	
	20	50	100	20	50
Contraction (III)	0.0400	0.0400	0.0400	0.0400	0.0400
Test Section (II)	0.0625	0.0575	0.0525	0.0536	0.0466
Diffuser (IV + V)	0.1429	0.1414	0.1400	0.1118	0.1109
Elbow (VI)	0.0051	0.0050	0.0050	0.0358	0.0356
Downcomer (VII)	0.0012	0.0011	0.0011	0.0080	0.0073
Elbow (VIII)	0.0058	0.0058	0.0058	0.0411	0.0411
Diffuser (VIII)	0.0082	0.0082	0.0082	0.0582	0.0580
Lower Leg (IX)	0.0039	0.0038	0.0037	0.0266	0.0260
Elbow (X)	0.0042	0.0042	0.0042	0.0326	0.0326
Upcomer (X)	0.0001	0.0001	0.0001	0.0008	0.0007
Elbow + Diffuser + Air Separator (X + XI + XII)	0.0053	0.0053	0.0053	0.0375	0.0375
ΣK_o Bare Channel	0.2792	0.2724	0.2659	0.4460	0.4363
ΣK_o With Test Body	0.3630	0.3562	0.3497	0.5178	0.5081
Energy Ratio Bare Channel	0.367	0.358	0.350	0.586	0.575
Energy Ratio With Test Body	0.478	0.468	0.460	0.680	0.668

Fig. 22 - Estimated Energy Loss Coefficients for the Prototype Facility

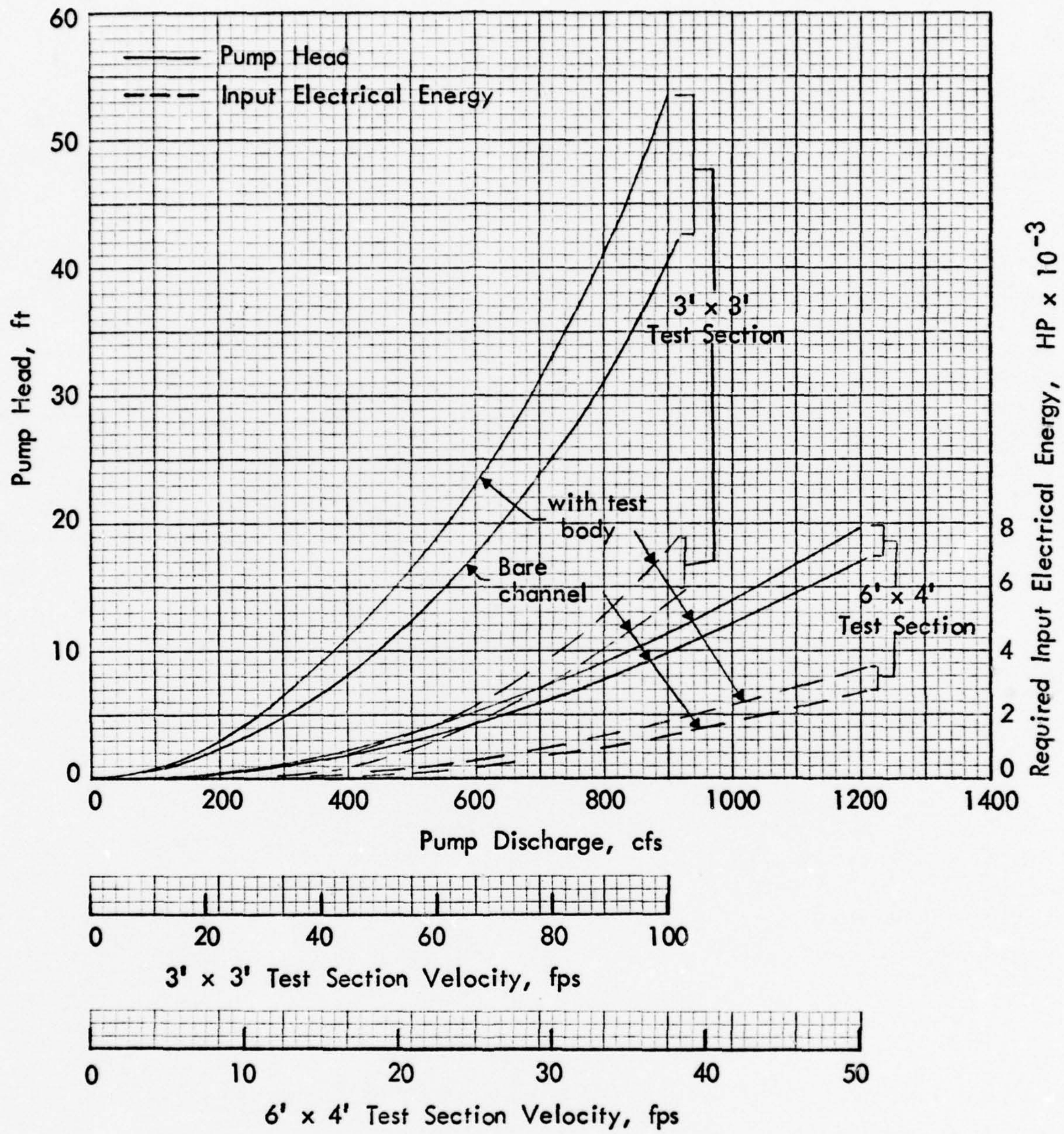


Fig. 23 - Estimated Discharge, Head, and Power Requirements for the Prototype Pump

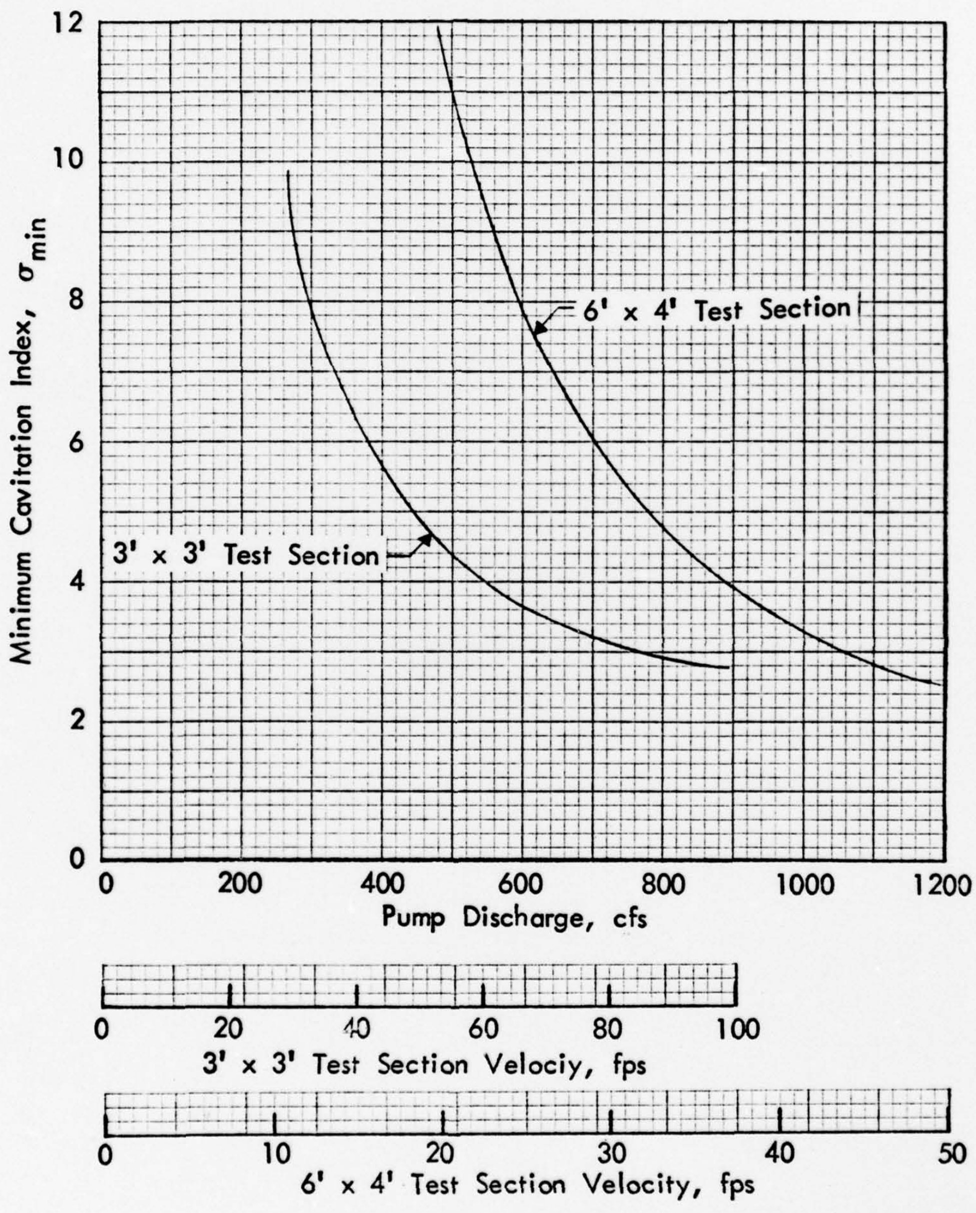


Fig. 24 - Estimated Minimum Cavitation Index Provided in Channel at Top of Prototype Pump Impeller

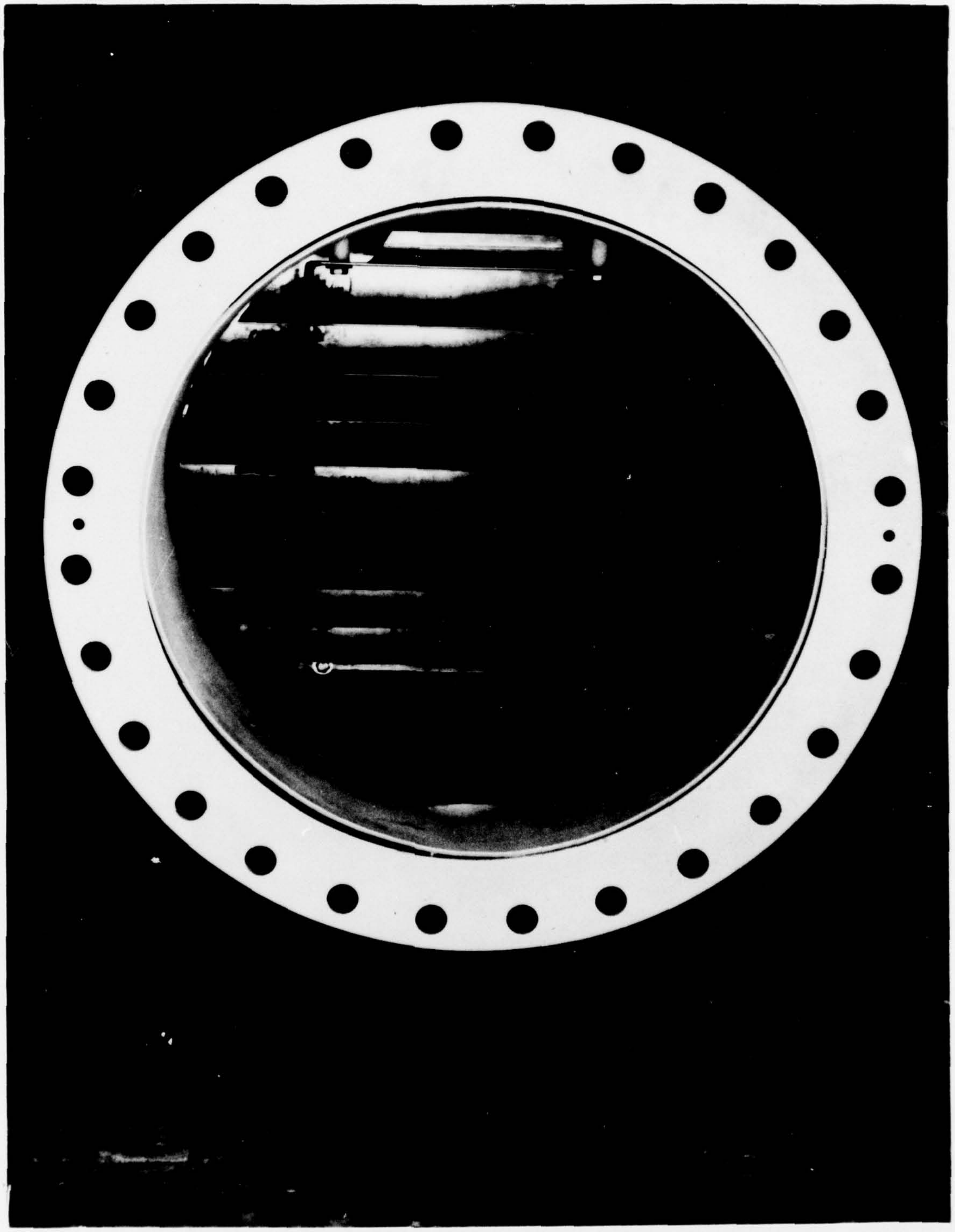


Fig. 25 - The Bent-Plane Vane Assembly in the Third Elbow of the model

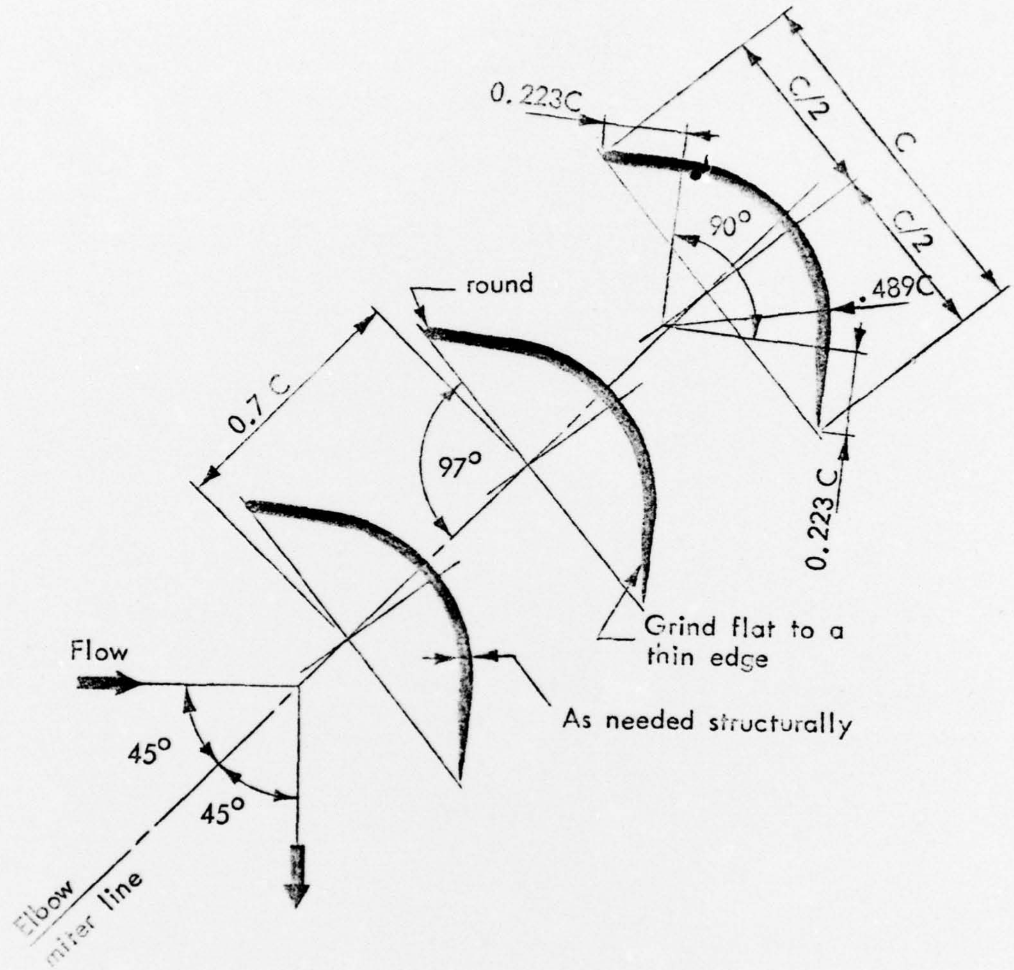


Fig. 26 - A General Detail for Bent-Plate Elbow Turning Vanes

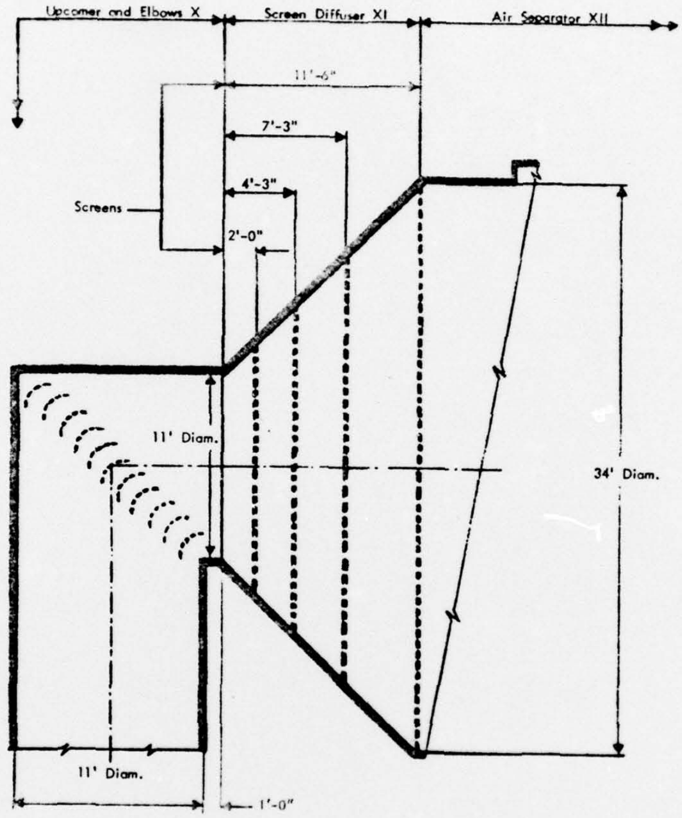
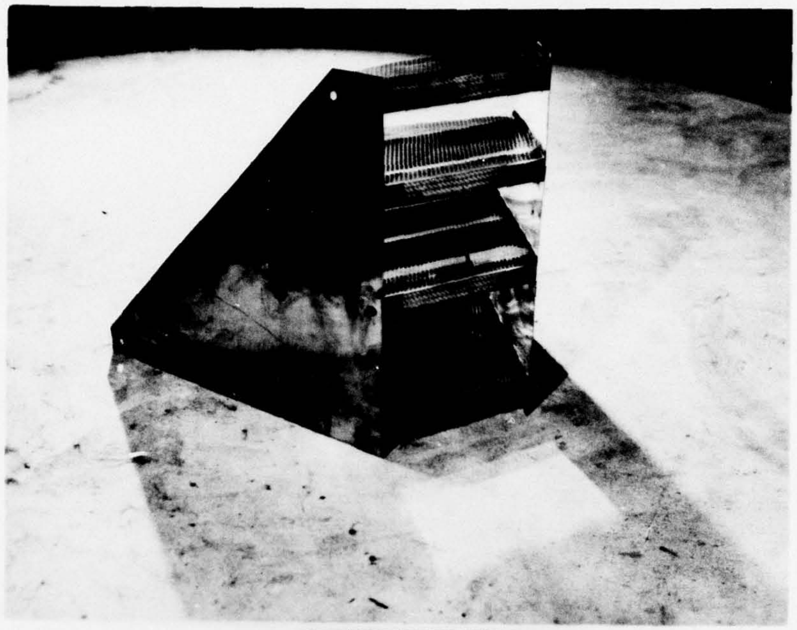
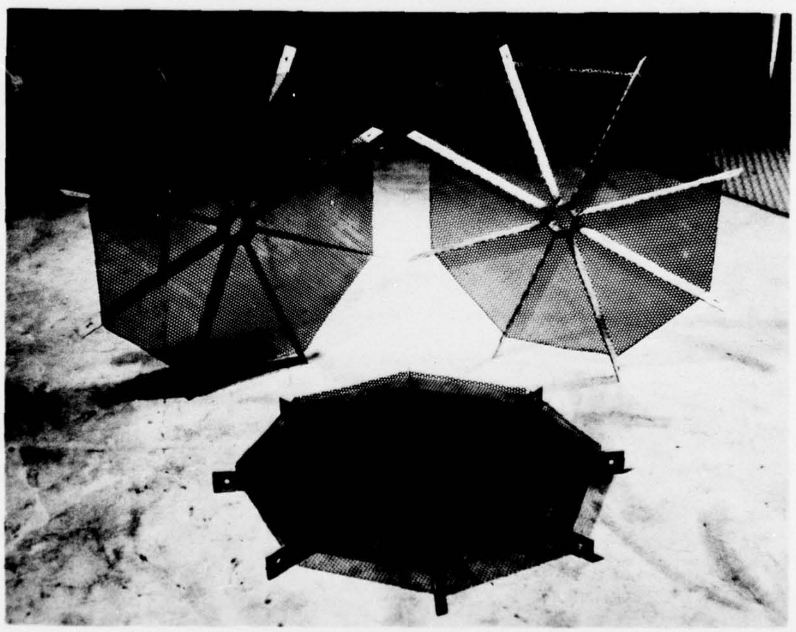


Fig. 27 - The Screen Diffuser Configuration (all dimensions relate to prototype inside flow surfaces)



(a) Four stage peripheral element (1 of 8)



(b) Single stage center element (4 units thus)

Fig. 28 - Prefabricated Elements of the Resistance Members of the Model Screen Diffuser

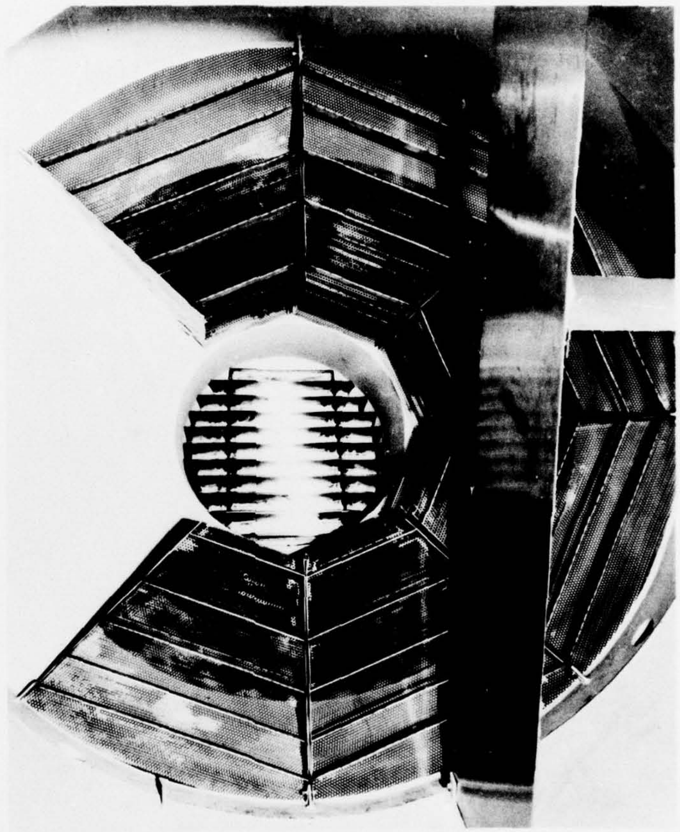


Fig. 29 - Partial Assembly of the Resistance Members of the Model Screen Diffuser (view looking upstream with separator support plates shown in right foreground)

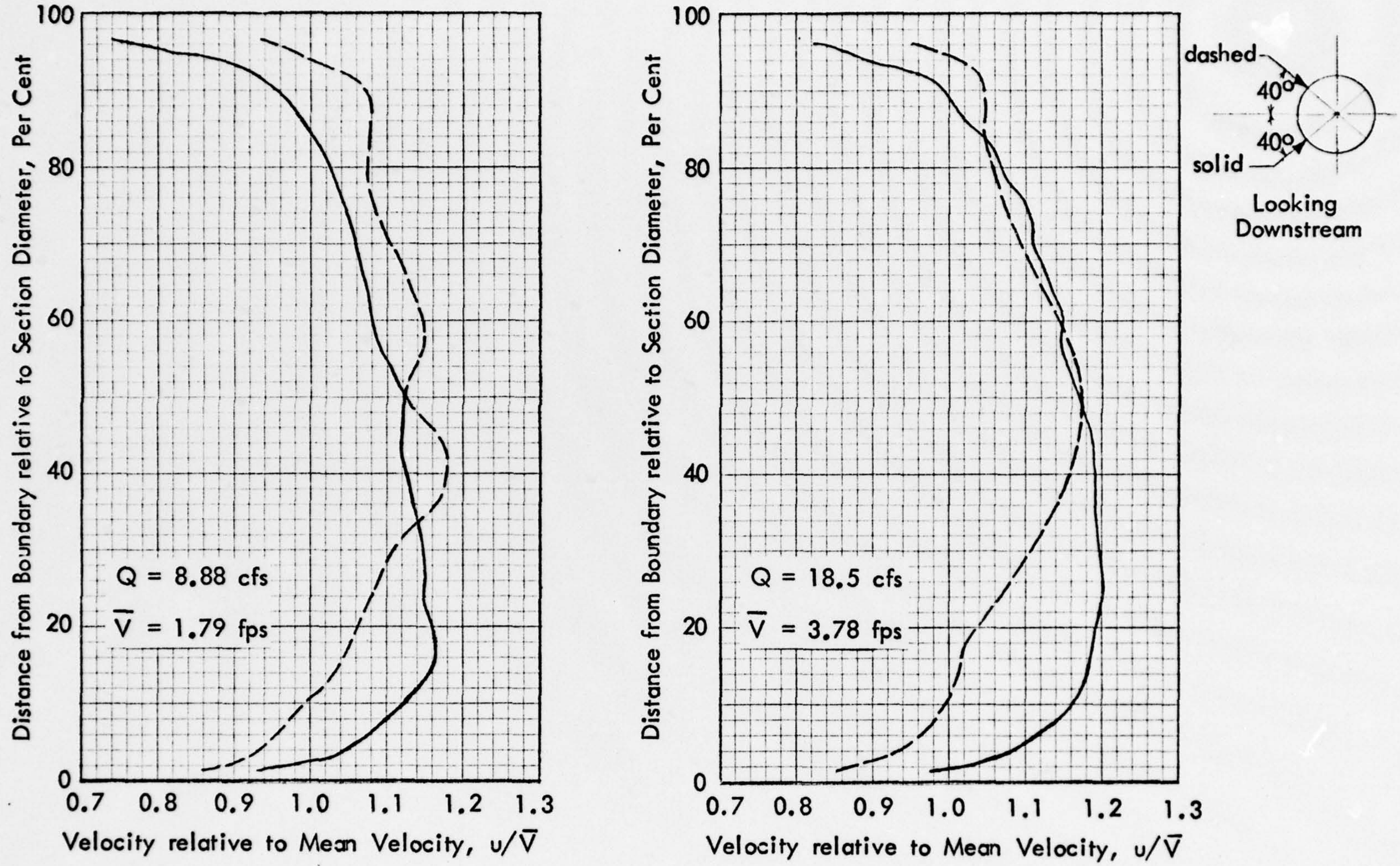


Fig. 30 - Velocity Profiles Ahead of Fourth Elbow in Model

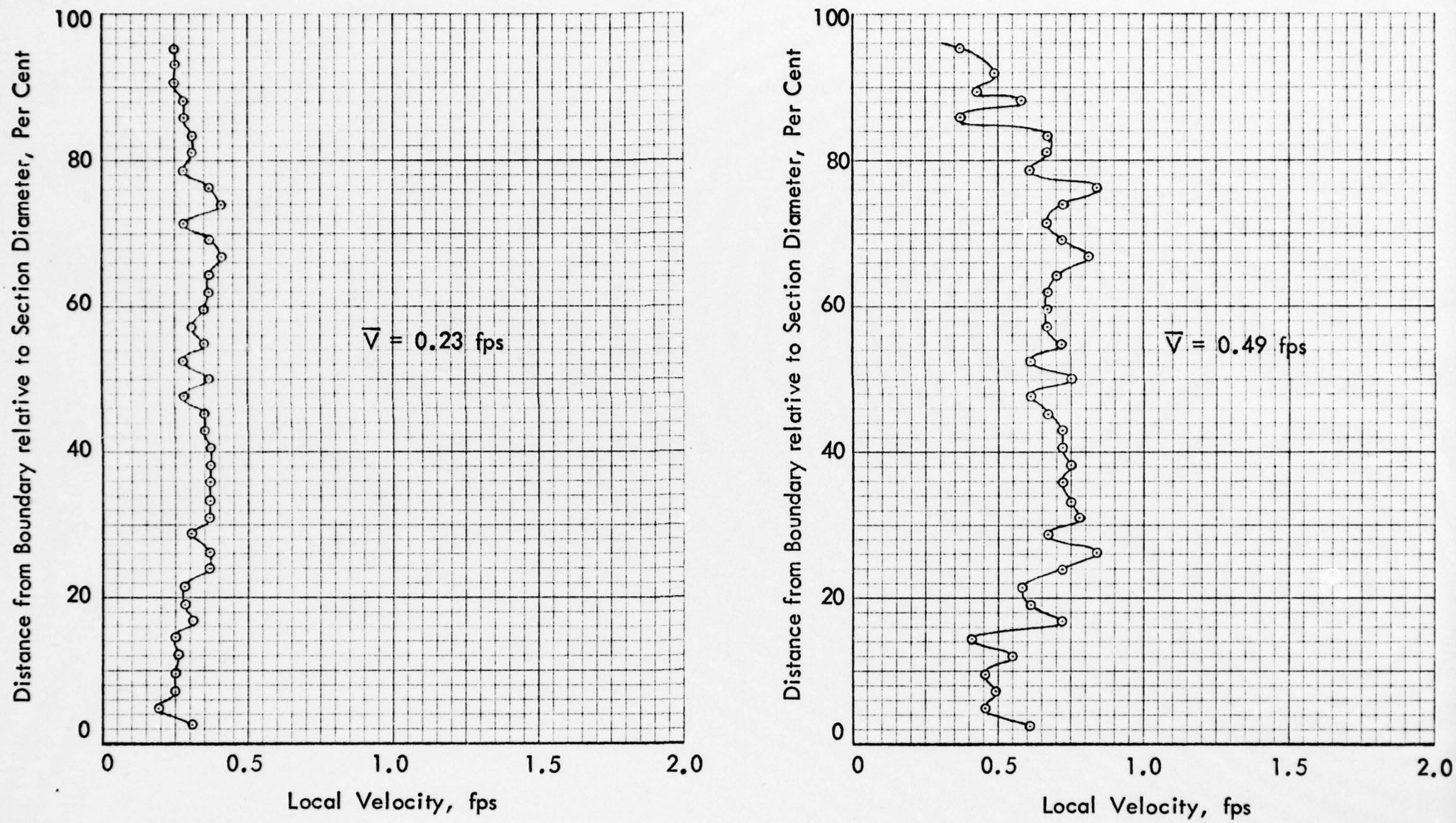


Fig. 31 - Velocity Profiles Just Downstream of Fourth Screen in Model Before Adjustment

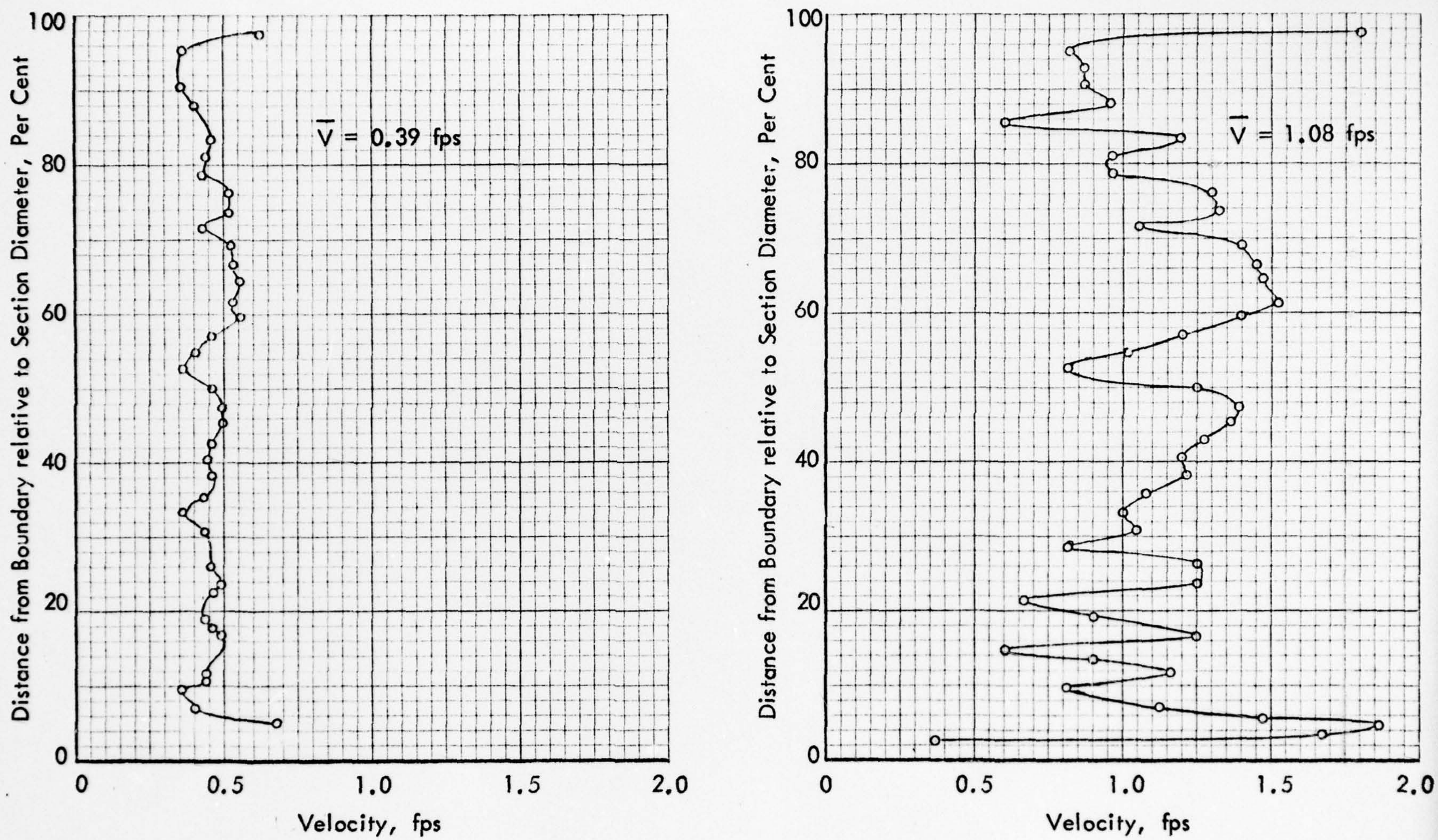


Fig. 32 - Velocity Profiles Just Downstream of Fourth Screen in Model After Adjustment

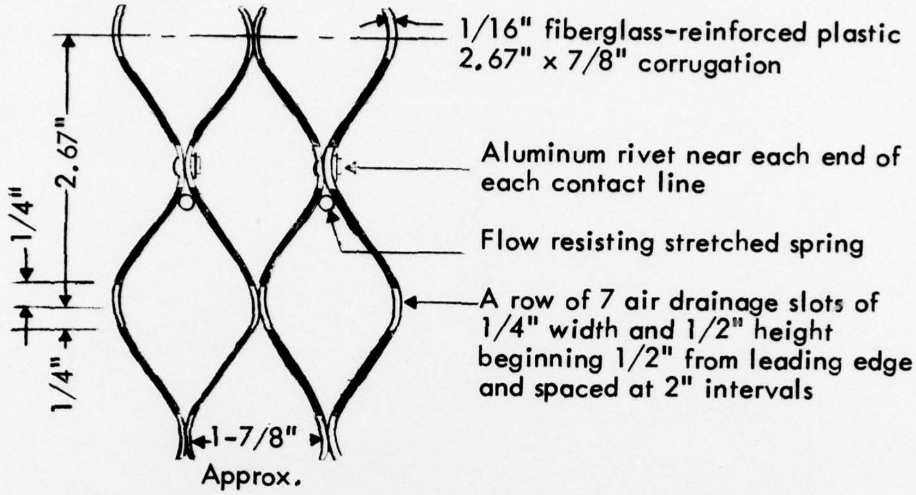


Fig. 33 - Air Separator Tube employed in Model Tests

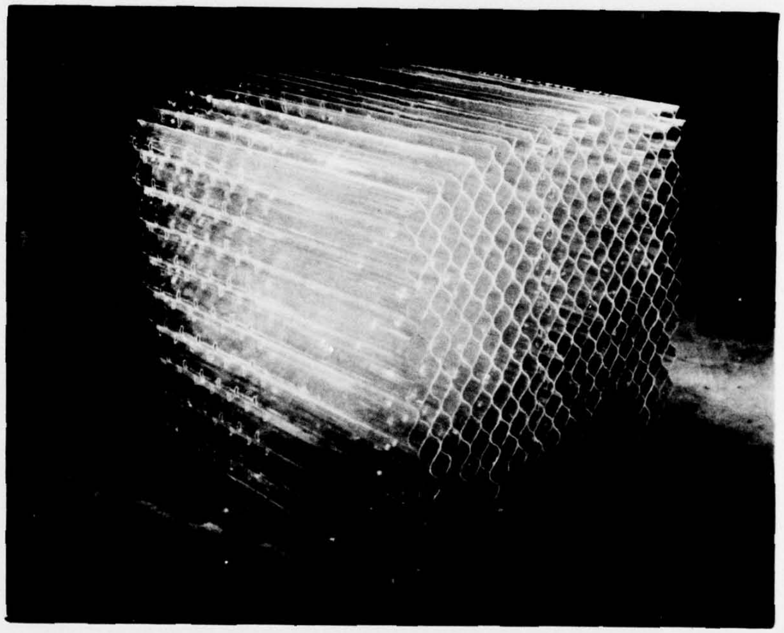


Fig. 34 - An Air Separator Tube Bundle as used in the Model

Fig. 35 - Partial Assembly of Roof Lip - Collection Lateral

Fig. 36 - Partial Assembly showing the Peripheral Air Collection Duct

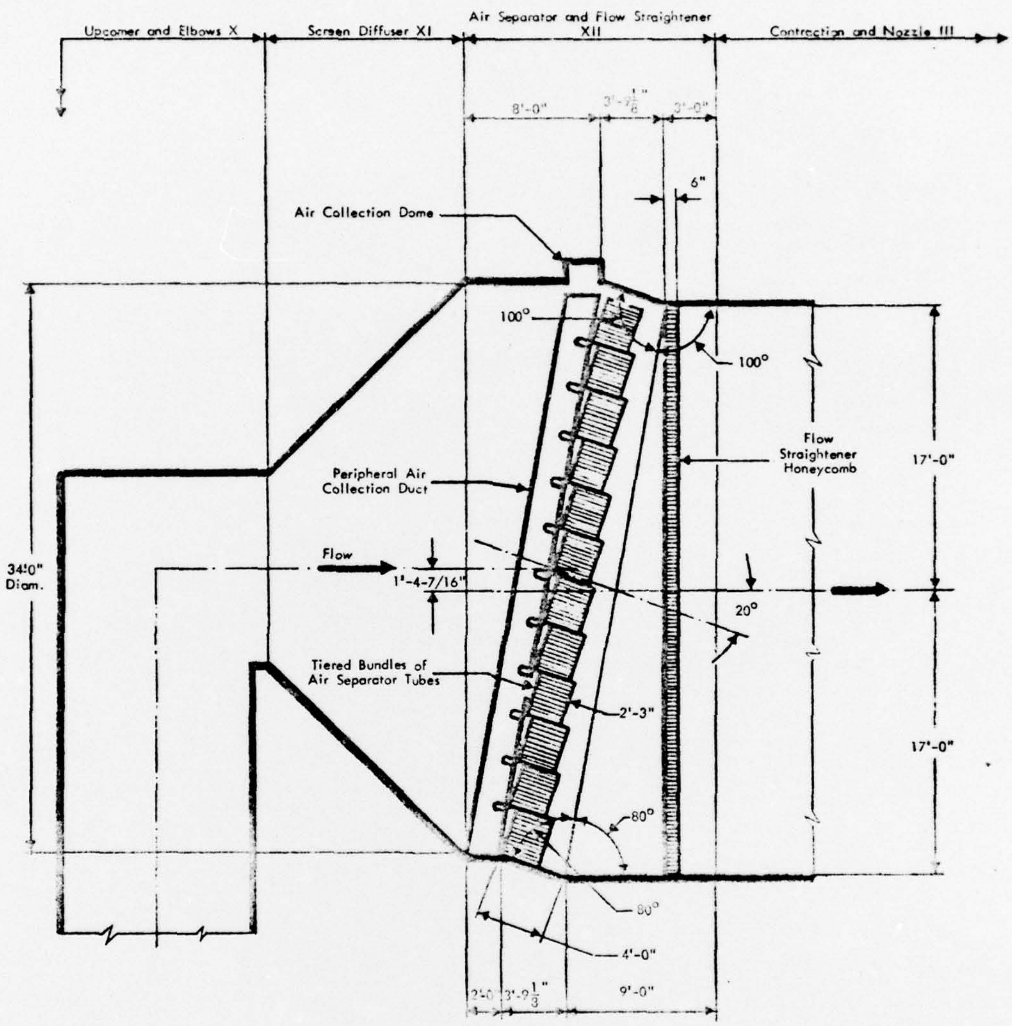


Fig. 37 - The Air Separator and Flow Straightener Configuration (all dimensions relate to prototype inside flow surfaces)

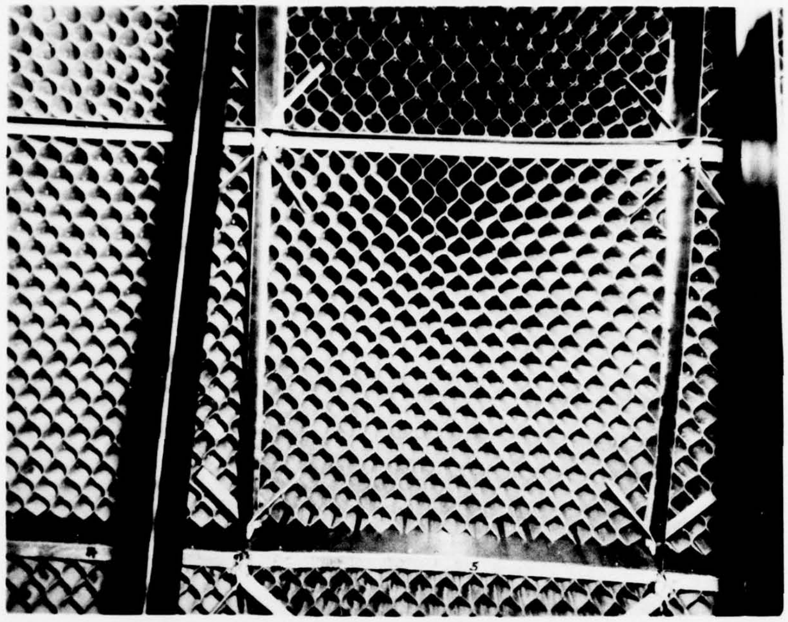
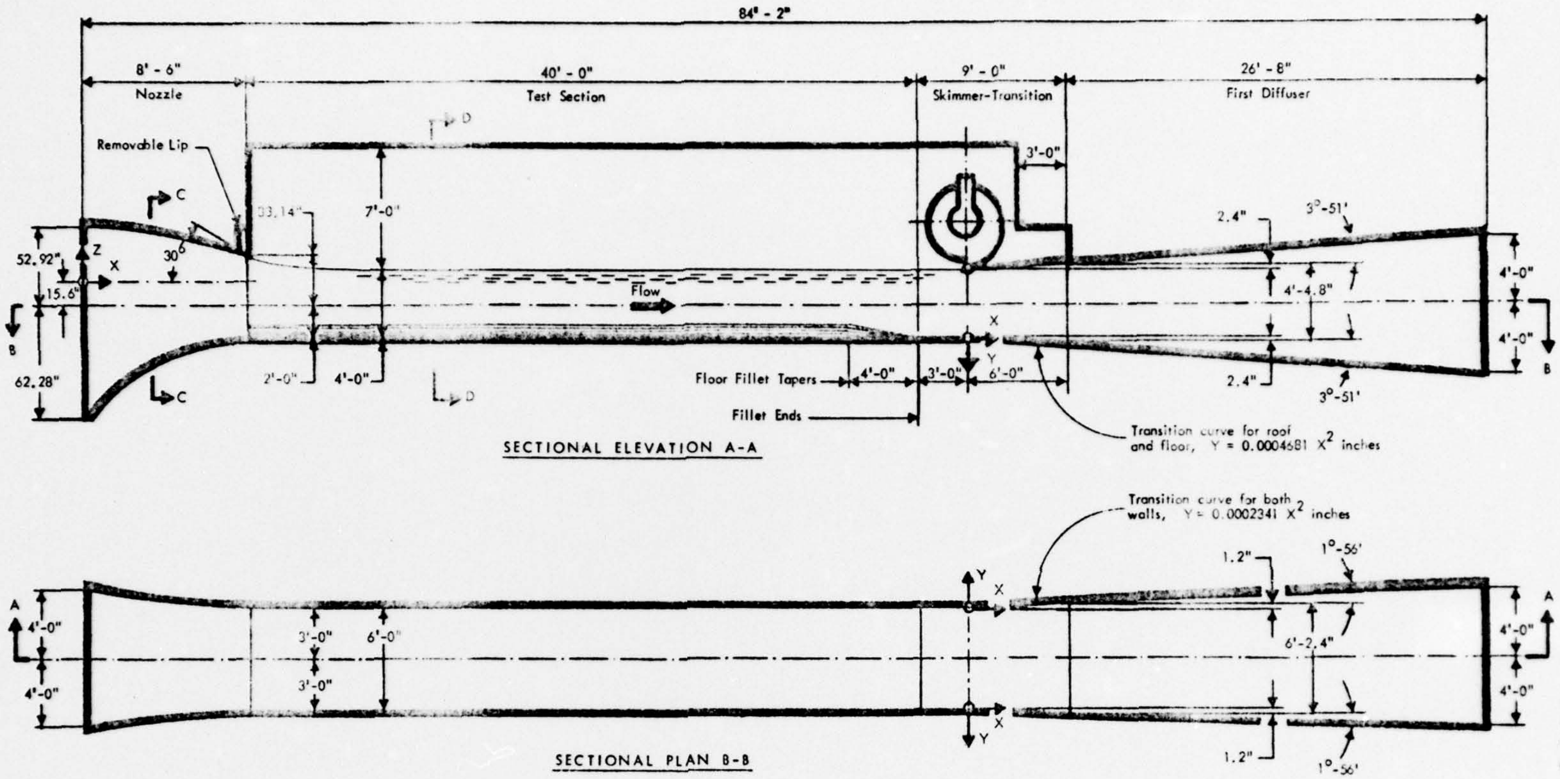
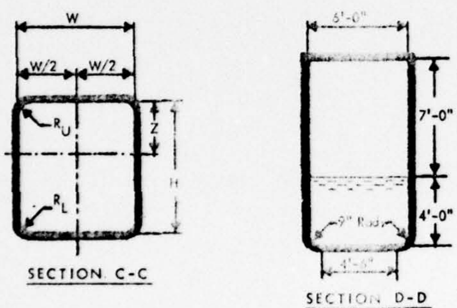


Fig. 38 - A Tiered Tube Bundle viewed from Downstream (showing added resistance angle along top, resistance material along sides, and restraining cleats in corners)

Component	Surface Finish (RMS)	Tolerances (inches)	Waviness (inches)
Contraction Nozzle			
a. Upstream half	250	± 1/8	.02 in 2" .10 in 10"
b. Downstream half	250	± 1/32	.01 in 2" .05 in 10"
Test Section	250	± 1/32	.01 in 2" .05 in 10"
Skimmer and Transition	250	± 1/8	.02 in 2" .10 in 10"
Main Diffuser	250	± 1/8	--
Vanes - First Elbow	250	± 1/32	--

Fig. 39 - Summary of Surface Finishes and Tolerances





NOZZLE DIMENSIONS - INCHES					
X	W	H	R_U	R_L	Z
0	96.00	115.20	30.00	30.00	37.32
10	89.30	107.61	24.85	25.75	37.30
20	84.71	100.96	20.76	22.56	37.16
30	81.25	94.68	17.22	19.92	36.80
40	78.54	89.03	14.07	17.67	36.08
50	76.41	83.73	11.20	15.70	34.91
60	74.76	78.63	8.59	13.96	33.15
70	73.53	73.59	6.16	12.46	30.69
80	72.67	68.49	3.94	11.14	27.43
90	72.17	63.20	0.083	9.96	23.24
100	72.00	57.40	0	9.00	18.00
100.8	72.00	57.14	0	9.00	17.54

Fig. 40 - The Alternate or Large Test Section Configuration (all dimensions relate to prototype inside flow surfaces)

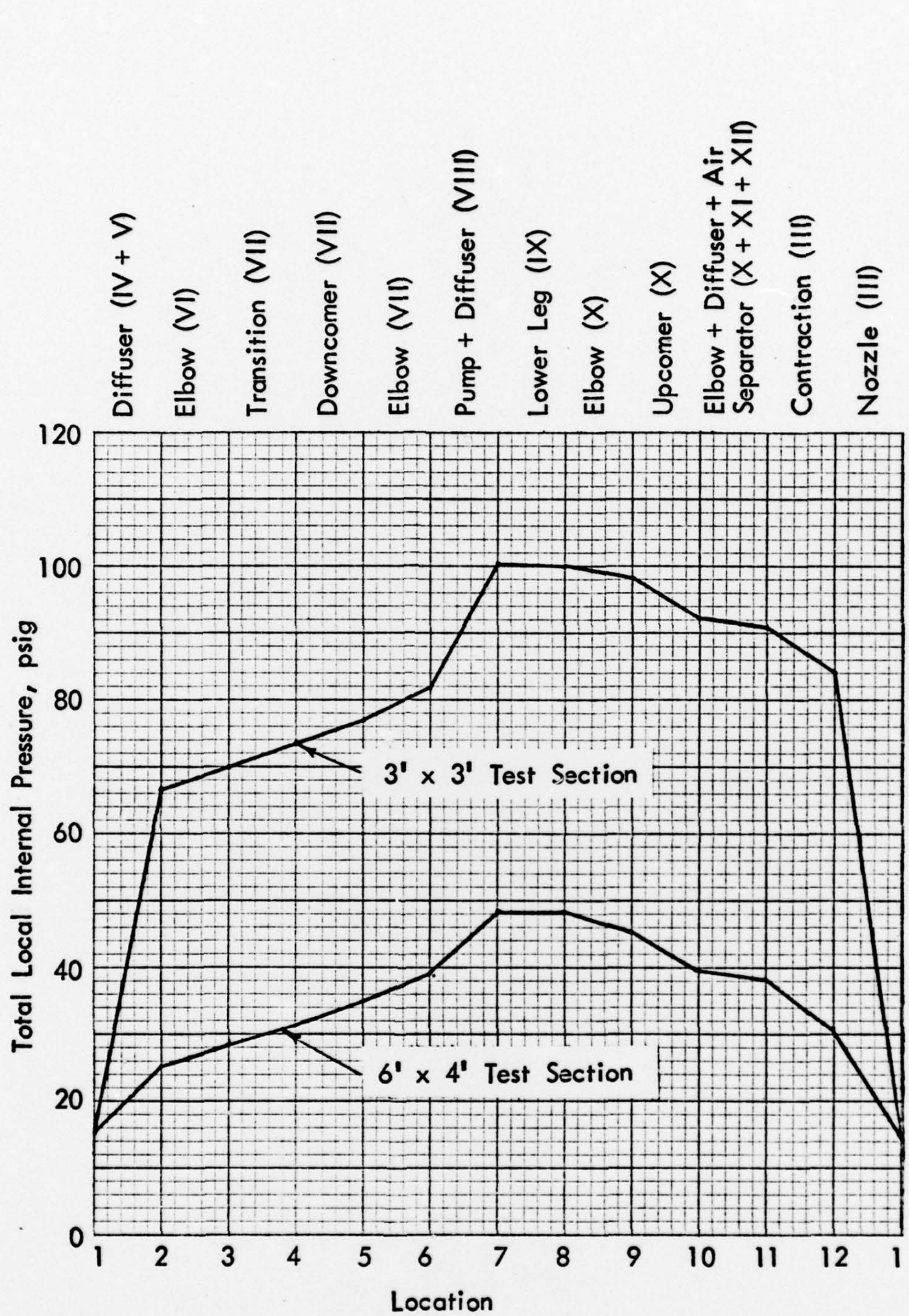


Fig. 41 - Internal Pressure in the Prototype Channel with One Atmosphere Surcharge Pressure and at Maximum Velocity